



**Politécnico
de Viseu**

Escola Superior
de Tecnologia
e Gestão de Viseu

Identification, Readiness and Potential of Technology Domains for Decarbonisation and the role of the Electric Power System

António Francisco Costa Duarte

Dissertação

Mestrado em Engenharia Eletrotécnica - Energia e Automação Industrial

Trabalho efetuado sob a orientação de

Professor Doutor Paulo Moisés Almeida da Costa
Professor Doutor Paulo Rogério Perfeito Tomé

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“Deus quer, o homem sonha, a obra nasce”

Fernando Pessoa

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ABSTRACT

The intensive use of fossil fuels in recent years has led to a significant increase in carbon dioxide (CO₂) levels in the atmosphere, contributing to global warming and its harmful effects on the climate. Global warming has become one of humanity's most urgent challenges. As a result, there is increasing pressure to reduce carbon emissions and take measures to limit the extent of climate change and its severe consequences.

This dissertation, developed under the research project “Sustainable Transformative Transitions - reconcile the acceleration of low carbon transitions with system transformations” – (PTDC/GES-AMB/0934/2020), funded by the Foundation for Science and Technology, focuses on the decarbonisation theme. Its content can be subdivided into two main parts.

In the first part, a methodology based on two text-mining tools was developed and applied to identify the domains of innovative decarbonisation technologies and instruments that have received significant attention from the scientific community in recent years. To achieve this, documents from databases of scientific publications (Scopus and Web of Science), research projects (Cordis), and patents (Patstat) were examined. Computational software was developed and used to process the outputs of the text-mining software and obtain a relevant set of terms related to decarbonisation technologies/instruments.

Those terms were then consolidated based on their characteristics to establish a set of 41 domains of technology/instruments that emerged as the most relevant to support the decarbonisation process. Analyses were carried out to assess the significance of these domains in scientific production by examining their relevance and occurrence, both in absolute and relative terms. The readiness of the domains was assessed by calculating the average technology readiness level (TRL) for a specific set of innovative technologies associated with each domain. This process was supported by information from a database provided by the International Energy Agency, which contained data on 368 distinct technology designs and components related to achieving net-zero emissions. The technologies of that database were categorised into specific domains based on their unique characteristics.

The domains were then intersected with six literature-derived decarbonisation pathways (defined elsewhere). This analysis revealed that twelve domains emerged as the more crucial in supporting these pathways. In addition, the risk levels for each pathway were determined based on the average Technology Readiness Level (TRL) and relevance-occurrence rank ratios. Furthermore, the potential for decarbonisation of each pathway was assessed using information

from the Intergovernmental Panel on Climate Change (IPCC) on the potential for reducing net carbon dioxide emissions (CO₂) by 2030.

The “Electrification of uses” pathway has emerged as the most promising for decarbonisation, demonstrating the highest readiness and average potential for CO₂ emissions reduction and a low-risk value. Furthermore, the “Decarbonisation of electricity” pathway ranks as the fourth most promising option. Consequently, the electrical sector plays a crucial role in achieving decarbonisation goals.

Based on these findings, the second part of this work concentrates on developing and applying a model to forecast avoided CO₂ emissions for the Portuguese power system until 2050. The model relies on predictions from reliable documents regarding electricity consumption and renewable electricity generation. Hence, four main scenarios were formulated to incorporate electricity consumption and production forecasts. Furthermore, these four scenarios were further categorised to include sub-scenarios related to different charging options for electric vehicles. It is essential to mention that these charging alternatives can significantly impact consumption patterns. The study also examined the effects on emissions due to incorporating storage systems into the electrical system. Additionally, it investigated how the distribution of renewable electricity production and storage systems across different networks within the electrical system influences emissions.

The results indicate that, in the base case study, significant values of avoided emissions can be expected from 2023 onwards. Depending on the scenario, the estimated avoided emissions for the 2023-2050 period ranges from 214.2 MtonCO₂ (low increase in electricity consumption and conservative growth in non-conventional generation scenario) to 266.5 MtonCO₂ (high increase in electricity consumption and ambitious increase in non-conventional generation scenario). The change in the consumption pattern due to the concentration of electric vehicle charging in specific periods (peak or night empty hours) revealed a reduction in the value of avoided emissions, which, in the most unfavourable scenario (represented by a high increase in electricity consumption and ambitious increase in non-conventional generation scenario), reaches 90.4% of the value obtained for the base scenario.

Integrating storage systems in the electric networks can potentially enhance the value of avoided emissions. The magnitude of this potential depends on various factors, including the specific scenario considered (in terms of consumption and generation), the indirect emissions associated with storage system manufacturing, and the changes in the load profile due to EV

charging. Moreover, the proper planning for storage capacity installation over the years and its location assumes a significant relevance on the value of avoided emissions, namely when considering the indirect emissions from manufacturing the storage systems. The results highlight that storage systems can increase the expected avoided emissions by up to 32.4%, depending on the scenario.

Furthermore, the results show that the distribution of the non-conventional generation across various networks directly impacts the expected avoided emissions.

Keywords: Avoided emissions; Bibliometric analysis; Decarbonisation; Technologies; Electric power sector; Portuguese electric system; Technology Readiness Level; Text-mining software

RESUMO

A utilização intensiva de combustíveis fósseis levou a um aumento significativo nos níveis de dióxido de carbono (CO₂) na atmosfera, contribuindo para o aquecimento global e consequentes efeitos nefastos sobre o clima. O aquecimento global tornou-se assim num dos desafios mais importantes para a humanidade, existindo uma pressão crescente para reduzir as emissões de gases com efeito de estufa, visando limitar a extensão das mudanças climáticas e das suas consequências. Esta dissertação, desenvolvida no âmbito do projeto de investigação “Transições Transformativas Sustentáveis - Conciliar a Aceleração das Transições para Baixo Carbono com Transformações do Sistema” - (PTDC/GES-AMB/0934/2020), financiado pela Fundação para a Ciência e Tecnologia, foca-se no tema da descarbonização. O seu conteúdo pode ser subdividido em duas partes principais.

Na primeira parte, foi desenvolvida uma metodologia, baseada em duas ferramentas de mineração de texto, destinada a permitir a identificação de domínios de tecnologias e de instrumentos de descarbonização que, nos últimos anos, têm recebido maior atenção da comunidade científica. As ferramentas de mineração de texto utilizadas permitiram a análise de um conjunto alargado de documentos obtidos em bases de dados de publicações científicas (Scopus e Web of Science), projetos de investigação (Cordis) e patentes (Patstat), visando a extração de termos relevantes. Estes termos foram posteriormente processados com recurso a programas computacionais desenvolvidos para o efeito, obtendo-se os termos relevante. Estes termos foram em seguida consolidados num conjunto de 41 domínios de tecnologias/instrumentos que emergiram como os mais relevantes para a descarbonização.

Foram realizadas análises para avaliar a importância dos domínios definidos no contexto da produção científica. Essas análises utilizaram dois indicadores fornecidos pelos programas de mineração de texto: a relevância e a ocorrência. Os indicadores foram avaliados tanto em termos absolutos quanto relativos. Além disso, o estado de prontidão dos domínios foi avaliado calculando-se o valor médio de prontidão tecnológica (TRL) das tecnologias associadas a cada domínio. Essa avaliação foi baseada em informações sobre 368 tecnologias e processos relacionados com o objetivo de alcançar emissões líquidas nulas, fornecidas pela Agência Internacional de Energia. Essas tecnologias foram associadas aos diferentes domínios com base nas suas características específicas.

A intersecção do conjunto dos domínios com um conjunto de seis estratégias para a descarbonização derivadas da literatura (num trabalho distinto) permitiu inferir os 5 domínios

mais relevantes para o desenvolvimento de cada estratégia. Importa realçar que, dos 41 domínios inicialmente definidos, apenas doze integraram o conjunto dos mais relevantes. A análise dos conjuntos de 5 domínios mais relevantes para cada estratégia de descarbonização permitiu a definição de um nível de risco para estas. Essa análise incluiu informações sobre os níveis de prontidão e de relevância/ocorrência dos referidos domínios. Além disso, o potencial de descarbonização de cada estratégia foi avaliado com base nas informações fornecidas pelo Painel Intergovernamental sobre Alterações Climáticas (IPCC) sobre o potencial de diversas tecnologias para reduzir as emissões de CO₂ até 2030.

A informação obtida para cada estratégia de descarbonização, nomeadamente no que se refere à prontidão, risco e potencial de descarbonização permitiu inferir que a estratégia denominada “Eletrificação dos usos” emergiu como a mais promissora para a descarbonização, demonstrando a maior prontidão e potencial médio de redução de CO₂ e o menor nível de risco. Por outro lado, a estratégia “Descarbonização da eletricidade” emergiu como a quarta opção mais promissora. Consequentemente, o setor elétrico assoma como crucial na consecução dos objetivos de descarbonização, pelo menos no curto prazo.

As conclusões sobre o sistema elétrico deram o mote para a segunda do trabalho, a qual se concentrou no desenvolvimento e aplicação de um modelo destinado a estimar as emissões evitadas de CO₂ para o sistema elétrico português até 2050. O modelo desenvolvido utilizou um conjunto de quatro cenários principais para acomodar as previsões relativas à evolução do consumo e de produção renovável de eletricidade. Além disso, foram ainda definidos três sub-cenários para incluir a influência de diferentes padrões de carregamento de veículos elétricos.

O modelo desenvolvido também permite avaliar os efeitos nas emissões originados pela incorporação nas redes elétricas de sistemas de armazenamento de energia. Além disso permite avaliar a influencia nas emissões evitadas resultante da forma como são distribuídas as capacidade da produção renovável de eletricidade e dos sistemas de armazenamento ao longo das diversas redes elétricas.

A aplicação do modelo desenvolvido permitiu estimar que, dependendo do cenário, as emissões evitadas para o período 2023-2050 variam entre 214,2 MtonCO₂ (cenário com pequeno aumento no consumo de eletricidade e crescimento conservador na produção não convencional) e 266,5 MtonCO₂ (cenário com grande aumento no consumo de eletricidade e crescimento ambicioso na produção não convencional). A mudança no perfil de consumo devido à concentração do carregamento de veículos elétricos em períodos específicos (horas de

ponta ou horas do vazio) revelou uma redução no valor de emissões evitadas. No cenário mais desfavorável (representado por grande aumento no consumo de eletricidade e crescimento ambicioso na produção não convencional), essa redução atinge 90,4% do valor obtido para o cenário base.

Os resultados mostram que a integração de sistemas de armazenamento nas redes elétricas pode potencializar as emissões evitadas. Esse potencial é, contudo, dependente de vários fatores, incluindo o cenário específico considerado, as emissões indiretas associadas à fabricação dos sistemas de armazenamento e as mudanças no perfil de carga devido ao carregamento de VE.

O planejamento adequado da instalação de capacidade de armazenamento ao longo dos anos bem como da respetiva localização no seio das redes elétricas assumem uma relevância significativa no valor de emissões evitadas. Esta influência é especialmente notória quando são internalizadas as emissões indiretas decorrentes da fabricação dos sistemas de armazenamento. Os resultados evidenciam que os sistemas de armazenamento podem aumentar as emissões evitadas esperadas em até 32,4% em 2050, dependendo do cenário.

Além disso, os resultados mostram também que a forma como a produção não convencional é distribuída ao longo das várias redes do sistema elétrico impacta diretamente no valor esperado para as emissões evitadas.

Palavras-chave: Análise bibliométrica; Descarbonização; Emissões evitadas; Nível de prontidão tecnológica; Sistema elétrico português; Sistema elétrico de potência; Software de mineração de texto; Tecnologia

GENERAL INDEX

LIST OF TABLES	xiv
LIST OF FIGURES	xvi
LIST OS ACRONYMS / ABBREVIATIONS	xxiii
1. INTRODUCTION	1
1.1. Framework.....	1
1.2. Objectives	7
1.3. Dissertation structure	8
1.4. Publication	9
2. IDENTIFICATION OF DECARBONISATION TECHNOLOGY DOMAINS ...	11
2.1. Related works	11
2.2. Methodology	13
2.2.1. Approach.....	13
2.2.2. Obtention of raw terms.....	15
2.2.2.1. Search string construction	15
2.2.2.2. Documents obtention	16
2.2.2.3. Bibliometric analysis.....	19
2.2.3. Obtention of final terms.....	21
2.2.4. Technology domains.....	26
2.2.4.1. Definition of technology domains	26
2.2.4.1. Assessment of relevance and occurrence	27
3. ASSESSMENT OF READINESS, RISKS, AND POTENTIAL OF DECARBONISATION PATHWAYS	36
3.1. Metric for measuring technology readiness.....	37
3.2. Innovative technologies for decarbonisation	40
3.3. Maturity of the technologies.....	48
3.3.1. Global analysis.....	48
3.3.2. Supply-side technologies	53
3.3.3. Demand-side technologies.....	56
3.3.3.1. Industry sector	57
3.3.3.2. Transport sector	60
3.3.3.3. Buildings sector	62
3.3.4. Maturity of carbon capture technologies	65
3.3.5. Maturity of the technologies according to their granularity.....	69
3.3.6. Maturity of technologies by energetic vector.....	71
3.4. Assessment of decarbonisation strategies	76

3.4.1.	Readiness of technology domains.....	76
3.4.2.	Readiness, risk and potential of decarbonisation strategies.....	80
3.4.2.1.	Decarbonisation strategies	80
3.4.2.2.	Assessment of the decarbonisation strategies' maturity	81
3.4.2.3.	Assessment of the risk of the decarbonisation pathways	82
3.4.2.4.	Assessment of the potential of the decarbonisation pathways	84
3.4.2.5.	Global performance	85
4.	METHODOLOGY FOR EVALUATING AVOIDED EMISSIONS IN AN ELECTRICAL POWER SYSTEM.....	87
4.1.	Related works	87
4.2.	Model to assess avoided emissions	88
4.3.	Inclusion of energy storage systems.....	97
5.	CASE STUDY	117
5.1.	Characterization of the Portuguese power system.....	117
5.1.1.	Electricity consumption	117
5.1.2.	Electricity generation.....	118
5.2.	Scenarios for energy generation and consumption	121
5.2.1.	Installed generation capacity scenarios.....	122
5.2.2.	Electricity consumption scenarios	124
5.2.3.	Global scenarios.....	125
5.2.4.	Generation and consumption profiles	128
5.2.4.1.	Generation profiles	128
5.2.4.2.	Consumption profile	131
5.2.4.3.	Impact of profiles on global scenarios.....	137
5.3.	Location of generation and consumption across the system	138
5.3.1.	Consumption.....	138
5.3.2.	Generation.....	138
5.4.	Loss factors	139
5.5.	Emission factors.....	143
5.6.	Storage systems.....	144
5.7.	Results	145
5.7.1.	System with the base consumption profile and without storage.....	145
5.7.2.	System with the base consumption profile and storage	146
5.7.3.	Influence of load profiles	153
5.7.3.1.	System without storage.....	153
5.7.3.2.	System with storage	155
5.7.4.	Influence of the generation distribution across the networks	159

5.7.5.	Influence of the storage systems distribution across the networks.....	165
5.7.6.	Indirect emissions of the storage systems.....	171
5.7.7.	The potential of the transport sector to avoid emissions	180
6.	CONCLUSIONS AND FUTURE WORKS.....	185
	BIBLIOGRAPHIC REFERENCES.....	193
	APPENDIXES	1
	APPENDIX A – Description of the bibliometric analysis tools (TIM and VOSviewer)..	2
	TIM – “Tools for Innovating Monitoring”	2
	VOSviewer.....	9
	ANNEXES.....	1
	ANNEX A – IEA innovative decarbonisation technologies.....	2

LIST OF TABLES

Table 1 - Terms related to decarbonization resulting from the literature review.....	15
Table 2 - Examples of normalised terms.....	22
Table 3 - Domains	27
Table 4 - Summary of the supply-side technologies	45
Table 5 - Summary of demand-side technologies in the Industry sector	47
Table 6 - Summary of demand-side technologies in the Transport sector.....	47
Table 7 - Summary of demand-side technologies in the Buildings sector.....	48
Table 8 - Technologies included in the Infrastructure group	51
Table 9 - Maturity assessment for the different segments of the supply side	54
Table 10 - Maturity assessment for the different segments of the industry subsector	58
Table 11 - Maturity assessment for the different segments of the transport subsector	61
Table 12 - Maturity assessment for the different segments of the buildings subsector	63
Table 13 - Number of technologies according to the granularity	69
Table 14 - Maturity assessment by energy vector	73
Table 15 - Typology, dimensions and description of Pathways for decarbonisation	80
Table 16 - Five most significant technology domains associated with decarbonisation pathways	81
Table 17 - Risk of the decarbonising pathways	84
Table 18 - Summary of results of each decarbonisation pathway.....	86
Table 19 - Variation in installed power generation capacity (2012-2022)	119
Table 20 - Energy generation and consumption in Portuguese electric system (2012-2022)	121
Table 21 - Summary of the scenarios' nomenclature.....	137
Table 22 - Energy consumption on the various voltage levels of the power system	138
Table 23 - Location of generation technologies across the various voltage levels of the electric system.....	139

Table 24 - Percentage of total losses that are fixed losses	141
Table 25 - Assumed values for the k factor.....	142
Table 26 - Assumed emission factors	143
Table 27 - Distribution of storage capacity through the various voltage levels – Base situation	145
Table 28 - Adopted Storage distribution for the different cases	165
Table 29 - Petrol and diesel emission factors and densities	183
Table 30 - Summary of results of each decarbonisation pathway.....	189
Table 31 - Most important fields in TIM search	3
Table 32 - Term Modifiers	4
Table 33 - Possible views of TIM software	5

LIST OF FIGURES

Figure 1 - EROI for discoveries for the U.S. of Oil and Gas Industry (Source: [8])	2
Figure 2 - Hydrocarbon consumption through time (Source: [9])	3
Figure 3 - Evolution of fossil energy consumption and GDP (Source: [11], [12]).....	3
Figure 4 - Evolution of global CO ₂ emissions (Source: [15]).....	4
Figure 5 - Relationship between temperature rise and various gases (Source: [14]).....	5
Figure 6 - GHG emissions by sector (Source: [21]).....	6
Figure 7 - Article published and indexed in IEEE Xplore® (Source: [34]).....	10
Figure 8 - Methodology for bibliometric analysis	14
Figure 9 - Search in TIM.....	17
Figure 10 - Search in WoS	17
Figure 11 - Extract from the documents retrieved by WoS	18
Figure 12 - Extract from the dataset retrieved by TIM for the year 2018.....	18
Figure 13 - Number of documents retrieved by TIM and WoS	19
Figure 14 - Obtention of keywords and their occurrence in VOS software.....	19
Figure 15 - Obtention of keywords and their relevance in TIM software.....	20
Figure 16 - Number of keywords retrieved from TIM and VOSviewer	21
Figure 17 - Procedure to create the semantic dictionary	23
Figure 18 - Filtering process for the dictionary.....	24
Figure 19 - Evolution of the making of the semantic dictionary	25
Figure 20 - Extract of the semantic dictionary	25
Figure 21 - Filtering process that supported the definition of the domains	26
Figure 22 - Relevance values	28
Figure 23 - Occurrence values	28
Figure 24 - Approach to rank the domains.....	29
Figure 25 - Rank of technologies domains.....	29

Figure 26 - Normalised relevance	30
Figure 27 - Normalised occurrence	30
Figure 28 - Variation of the average value of relevance	31
Figure 29 - Variation of the average value of occurrence	32
Figure 30 - Accumulated Relevance – Top 20 ranked domains	33
Figure 31 - Accumulated Occurrence – Top 20 ranked domains	33
Figure 32 - Relative accumulated relevance	34
Figure 33 - Relative accumulated occurrence	35
Figure 34 - TRL scale adopted by IEA (Source: [50]).....	38
Figure 35 - Correspondence between quantitative and qualitative TRL scales	39
Figure 36 - IEA innovative decarbonisation technologies (Source: [52])	40
Figure 37 - Extract of the IEA Excel file with information about innovative decarbonisation technologies.....	41
Figure 38 - Innovative technologies according to the side they are integrated.....	41
Figure 39 - Extract of technologies from the supply side group	42
Figure 40 - Extract of technologies from the demand side group – Industry sector	42
Figure 41 - Extract of technologies from the demand side group – Transport sector.....	43
Figure 42 - Extract of technologies from the demand side group – Buildings sector.....	43
Figure 43 - Extract of technologies from the CO ₂ infrastructure group.....	43
Figure 44 - Sectors of technologies on the supply side.....	44
Figure 45 - Sectors of technologies on the demand side.....	46
Figure 46 - Maturity of technologies according to the side of the system they belong	48
Figure 47 - Creation of an infrastructure-related technologies group	50
Figure 48 - Relative weight of Supply, Demand, and Infrastructures groups.....	51
Figure 49 - Maturity of technologies for demand-side, supply-side and infrastructure groups	52

Figure 50 - Technologies included in each segment of the supply side.....	53
Figure 51 - Maturity of the technologies of some segments of the supply side.....	54
Figure 52 - Maturity of technologies by demand side sector	56
Figure 53 - Technologies included in each segment of the industry sector	57
Figure 54 - Maturity of the technologies of some segments of the industry subsector.....	58
Figure 55 - Technologies included in each segment of the transport sector	60
Figure 56 - Maturity of the technologies of some segments of the transport subsector	61
Figure 57 - Technologies included in each segment of the buildings sector	63
Figure 58 - Maturity of the technologies of some segments of the buildings subsector.....	64
Figure 59 - Technologies included in each group of the carbon capture technologies	66
Figure 60 - Maturity of each group of carbon capture technologies	67
Figure 61- Number of avoided emissions technologies according to the side they belong to (supply/demand).....	67
Figure 62 - TRL of avoided emissions technologies according to the side they belong to (demand/supply side)	68
Figure 63 - TRL by granularity for the supply side	70
Figure 64 - Concept of energy vector.....	71
Figure 65 - Division of the vectors by side	73
Figure 66 - TRL of technologies according to the energy vector and side (supply or demand)	74
Figure 67 - Maturity of technology domains	78
Figure 68 - Domains classification according to the prevalence of supply-side or demand-side technologies.....	79
Figure 69 - Characterisation of Pathways' Readiness.....	82
Figure 70 - Suitability of domains to support decarbonisation	83
Figure 71 - Potential to reduce net CO ₂ emissions of each decarbonisation pathway	85
Figure 72 - Simplified power system	89

Figure 73 - Power system with several conventional power plants	92
Figure 74 - Power system with non-conventional generation distributed on the system.....	94
Figure 75 - Power system with storage systems	98
Figure 76 - Example of the mode of operation assumed for energy storage	99
Figure 77 - Algorithm to calculate the energy to be stored in each network level	103
Figure 78 - Example of the operation of discharging the storage	109
Figure 79 - Algorithm for computing the energy required from storage systems to satisfy consumption at each network p	114
Figure 80 - Historical electricity consumption in Portugal (source: [86])	117
Figure 81 - Installed capacity in the Portuguese electric power generation system (2012-2022)	118
Figure 82 - Electricity generation by technology in Portugal (2012-2022)	119
Figure 83 - Influence of productivity indexes of renewable generation on thermal-based generation	121
Figure 84 - Forecasted installed power on generation system – conservative scenario.....	123
Figure 85 - Forecasted installed power on generation system – ambition scenario.....	124
Figure 86 - Forecasts for electricity consumption – conservative and ambition scenarios..	125
Figure 87 - Scenarios regarding supply and demand	125
Figure 88 - Energy prospects of supply and demand sides according to the defined scenarios	127
Figure 89 - Data acquired from the system’s operator – example for 2022.....	128
Figure 90 - Generation profiles for three typical days of the winter season (January)	129
Figure 91 - Generation profiles for three typical days of the spring season (April)	130
Figure 92 - Generation profiles for three typical days of the summer season (July)	130
Figure 93 - Generation profiles for three typical days of the fall season (October)	131
Figure 94 - Consumption profile for two typical days of April	132

Figure 95 - Potential EV load profiles (uncontrolled on the left, concentrated on the night period in the middle, and with V2G on the right) (Source: [100]).....	133
Figure 96 - Forecasting for the number of electric vehicles circulating in Portugal.....	134
Figure 97 - Load profiles for three typical days of the winter season (January).....	135
Figure 98 - Load profiles for three typical days of the spring season (April).....	136
Figure 99 - Load profiles for three typical days of the summer season (July).....	136
Figure 100 - Load profiles for three typical days of the fall season (October)	137
Figure 101 - Extract of values for the loss adjustment factors – example for 2022.....	140
Figure 102 - Evolution of the LAF for the peak period (2015-2023)	140
Figure 103 - Extract of the calculated avoided losses factors	142
Figure 104 - Example of generation for emission factor calculation.....	143
Figure 105 - Expected avoided emissions – scenarios 1A, 2A, 3A and 4A.....	146
Figure 106 - Results of avoided emissions for scenarios 1A, 2A, 3A and 4A when storage capacity is considered.....	148
Figure 107 - Avoided emissions for scenario 1A – Storage capacity of 0, 10 and 400 GWh	149
Figure 108 - Avoided emissions for scenario 2A – Storage capacity of 0, 10 and 400 GWh	150
Figure 109 - Avoided emissions for scenario 3A – Storage capacity of 0, 10 and 400 GWh	150
Figure 110 - Avoided emissions for scenario 4A – Storage capacity of 0, 10 and 400 GWh	151
Figure 111 - Optimal storage capacity through the years for the different scenarios	152
Figure 112 - Influence of EV charging strategy on avoided emissions – system without storage	153
Figure 113 - Percentual difference in avoided emissions – consumption profiles B and C compared to consumption profile A.....	155
Figure 114 - Results of avoided emissions for scenarios 1B, 2B, 3B and 4B.....	156

Figure 115 - Results of avoided emissions for scenarios 1C, 2C, 3C and 4C.....	157
Figure 116 - Optimal storage capacity over the years for scenarios 1A, 1B and 1C	159
Figure 117 - Adopted proportion of installed PV power across the networks.....	160
Figure 118 - Evolution of installed PV power across the networks.....	161
Figure 119 - Avoided emissions gain due to higher concentration of PV generation in a system without storage	162
Figure 120 - Avoided emissions gain due to higher concentration of PV generation in a system with storage	164
Figure 121 - Impact on avoided emissions due to storage systems distributed according to the pattern of generation.....	167
Figure 122 - Impact on avoided emissions due to storage systems distributed according to the pattern of consumption.....	168
Figure 123 - Comparison between different distribution patterns of storage systems.....	170
Figure 124 - Results adjusted for indirect emissions associated with storage systems.....	173
Figure 125 - Influence of the indirect emissions range on the expected avoided emissions with 400 GWh of storage capacity	175
Figure 126 - Influence of the indirect emissions range on the expected avoided emissions with 100 GWh of storage capacity	176
Figure 127 - Results adjusted for indirect emissions and storage capacity distributed according to the generation pattern.....	178
Figure 128 - Influence of the indirect emissions range on the expected avoided emissions for 70 GWh capacity distributed according to the generation pattern	179
Figure 129 - Distribution of vehicles in Portugal categorized by the type of fuel.....	181
Figure 130 - Share in sales of gasoline and diesel vehicles *(2023 so far) (based on data from [149]).....	181
Figure 131 - Assumed tendency in the share of petrol and diesel vehicles	182
Figure 132 - Avoided emissions of the transport sector for Portugal's mainland.....	184
Figure 133 - Search on TIM.....	3

Figure 134 - Example of a dataset resulting from a TIM search.....	4
Figure 135 - Example of relevant keywords in a specific dataset.....	8
Figure 136 - View by location and countries in TIM software	8
Figure 137 - Search on WoS	9
Figure 138 - WoS exporting dataset.....	10
Figure 139 - Choosing the type of data in VOS software	10
Figure 140 - Data insertion in VOS software.....	11
Figure 141 - Choosing the type of analysis and counting method in VOS software	11
Figure 142 - Layout of VOS software.....	12
Figure 143 - Network view in VOS Software.....	13
Figure 144 - Overlay view in VOS software.....	13
Figure 145 - Density view in VOS software	14

LIST OS ACRONYMS / ABBREVIATIONS

BIPV – Building Integrated Photovoltaic

CCS – Carbon Capture and Storage

CCSU – Carbon Capture Storage and Utilisation

CH₄ – Methane

CHP – Combined Heat and Power

CO₂ – Carbon dioxide

CO₂-EOR – Carbon dioxide Enhanced Oil Recovery

DGEG – Direção Geral da Energia e Geologia (General Directorate of Energy and Geology)

DoD – Depth of Discharge

EROI – Energy Return On Investment

ERSE – Entidade Reguladora dos Serviços Energéticos (Regulatory entity for Energy Services)

EV – Electric Vehicle

FACTS – Flexible Alternated Current Transmission Systems

FAME – Fatty Acid Methyl Ester

FCT – Fundação para a Ciência e Tecnologia (Foundation for Science and Technology)

GDP – Gross Domestic Product

GHG – Green House Gases

GW – Gigawatt

H₂ – Hydrogen

H₂ BTL – Hydrogen

HV – High Voltage

HVAC – Heating, Ventilation and Air Conditioning

HVDC – High Voltage Direct Current

HVO – Hydrotreated Vegetable Oil

ICE – Internal Combustion Engine

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

kg – kilogram

kW – kilowatt

kWh – kilowatt-hour

LAF – Loss Adjustment Factors

LCA – Life Cycle Assessment

LED – Light Emitter Diode

LOHC – Liquid Organic Hydrogen Carrier

Li – Lithium

LOHC – Liquid Organic Hydrogen Carrier

LPG – Liquid Propane Gas

LV – Low Voltage

MIBEL – Mercado Ibérico da Energia Elétrica (Iberian Electricity Market)

MOMs – Magnesium Oxides derived from Magnesium Silicates

MtonCO₂ – Mega tonnes of carbon dioxide

MV – Medium Voltage

MW – Megawatt

MWh – Megawatt-hour

NASA – National Aeronautics and Space Administration

N₂O – Nitrous Oxide

NZE – Net Zero Emissions

OLED – Organic Light Emitter Diode

OpenADR – Open Automated Demand Response

P2P – Peer to Peer

PLED – Polymer Light Emitter Diode

PNEC – Plano Nacional da Energia e do Clima (National Energy and Climate Plan)

PV – Photovoltaic

REN – Redes Eléctricas Nacionais (National Electric Grids)

RNC – Roteiro para a Neutralidade Carbónica (Roadmap to Carbon Neutrality)

TF-IDF – Term Frequency - Inverse Document Frequency

THV – Transmission High Voltage

TIM – Tools for Innovation Monitoring

TRL – Technology Readiness level

TW – Terawatt

VHV – Very High Voltage

VOSviewer – Visualisation of Similarities viewer

WoS – Web of Science

1. INTRODUCTION

This chapter presents the central focus of this work, thereby offering a comprehension of the scope of the work undertaken. An overview of the objectives to be reached in this work is also presented.

1.1. Framework

Before the widespread use of oil, coal served as the predominant energy source for the industrial sector. However, the discovery and subsequent utilization of oil as an energy source brought a transformative shift in the industrial landscape. This pivotal shift occurred during the first industrial revolution, which commenced in the mid-18th century and extended until the mid-19th century.

Adopting oil as a primary energy source had far-reaching implications, spurring the development of innovative technologies and entire industries. Notably, it played a foundational role in the evolution of the transportation and petrochemical sectors. Moreover, the byproducts of oil refinement facilitated the creation of novel products such as plastics, synthetic fibres, and fertilizers, all of which contributed significantly to economic growth and diversification [1], [2].

In addition to the discovery and widespread use of oil, identifying natural gas as an energy source around the same period marked a significant milestone. Natural gas was particularly notable for its cleaner characteristics compared to other fossil fuels. Consequently, it found early applications in the lighting field and played a crucial role in developing innovations such as cooking stoves and heating systems for indoor environments. This transition to natural gas had significant implications for both public and residential infrastructure, enhancing the quality of life and comfort in many communities [3] – [5].

The revolutionary impact of oil and natural gas on the world can be attributed to several key factors. These include the ease of extraction, high energy density, and the versatility of oil in creating various other petrochemical elements [2], [6]. Additionally, natural gas gained prominence due to its ease of use in cooking and heating applications [5].

Furthermore, the favourable value of Energy Return on Investment (EROI)¹ for oil and natural gas played a significant role. These energy sources exhibited a consistently high EROI from the outset, as illustrated in Figure 1. This favourable EROI further facilitated their widespread adoption and transformative impact on various sectors of the global economy [7].

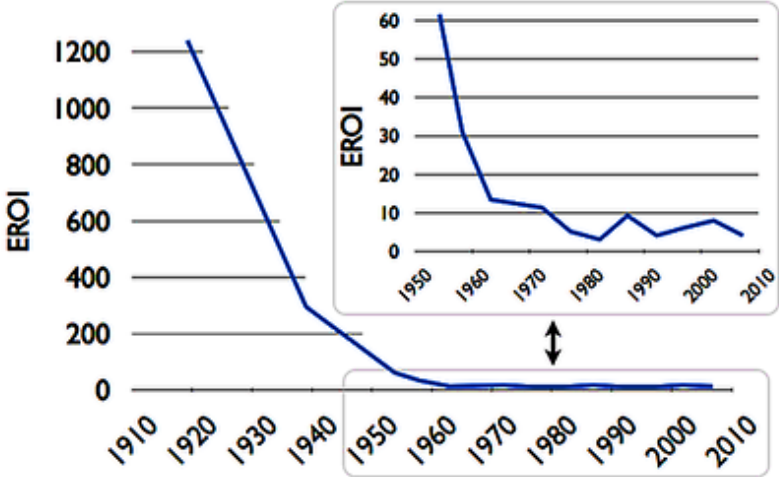


Figure 1 - EROI for discoveries for the U.S. of Oil and Gas Industry (Source: [8])

Hydrocarbon fuels, including coal, oil, and natural gas, substantially expanded in utilization and significance following World War I. These fuels became essential to human life, driving the global economy and playing a pivotal role in modern civilization. Notably, they contributed to lifting countless individuals out of poverty [9], [10].

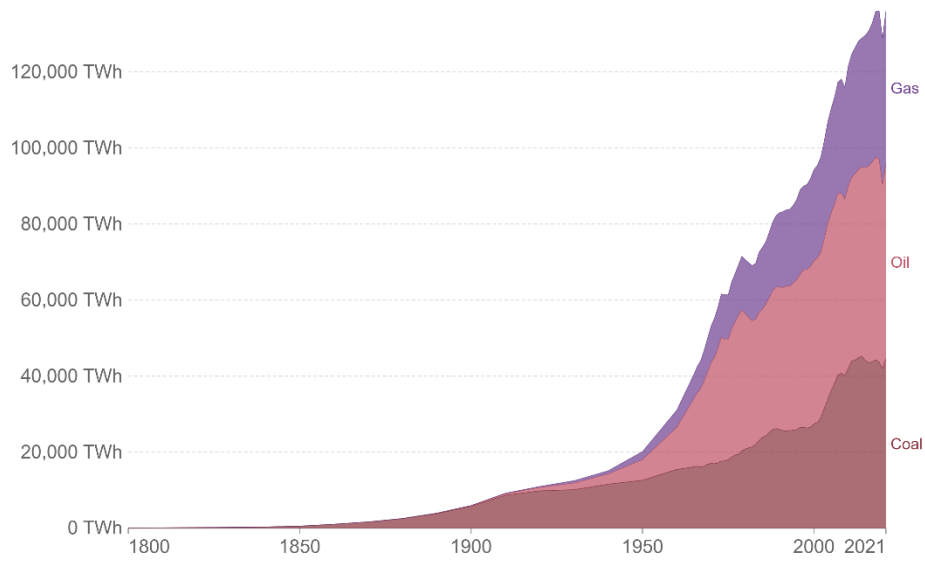
The consumption of fossil fuels (coal, oil, and natural gas) saw a dramatic increase after the end of World War I, as illustrated in Figure 2, marking a transformative era in energy consumption and economic development. Additionally, Figure 3 shows the historical evolution of fossil energy consumption alongside gross domestic product (GDP), demonstrating a decline in energy intensity over time.

¹ EROI is a ratio for describing a measure of energy produced in relation to the energy used to create it. For instance, the ratio would illustrate how much energy is used to locate, extract, deliver, and refine crude oil relative to how much useable energy is created. The EROI is a key determinant of the price of energy because sources of energy that can be tapped relatively cheaply will allow the price to remain low [158].

Global fossil fuel consumption

Global primary energy consumption by fossil fuel source, measured in terawatt-hours (TWh).

Our World
in Data



Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy OurWorldInData.org/fossil-fuels/ • CC BY

Figure 2 - Hydrocarbon consumption through time (Source: [9])

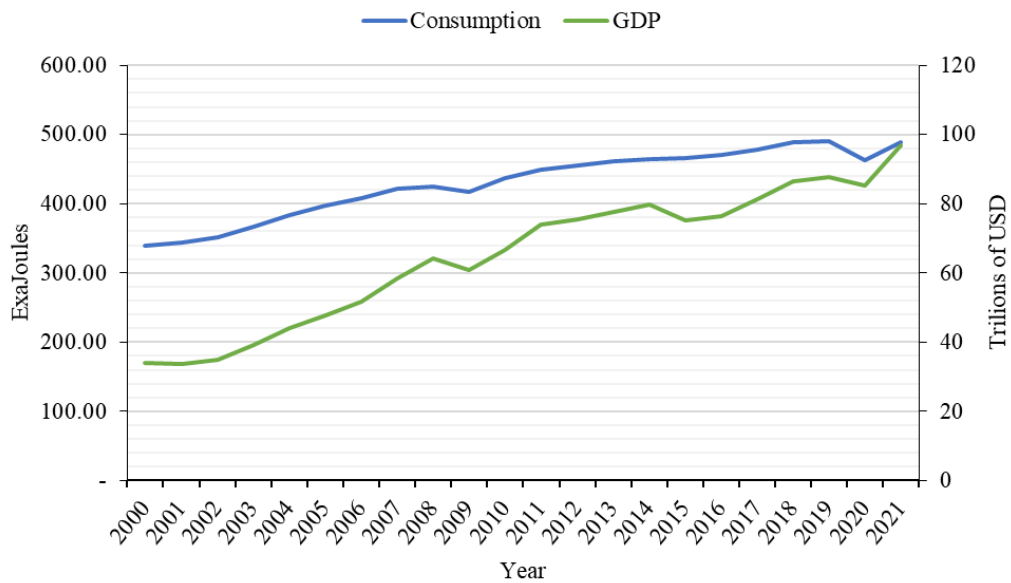


Figure 3 - Evolution of fossil energy consumption and GDP (Source: [11], [12])

Fossil fuels often involve combustion, leading to the release of greenhouse gases (GHGs)², namely carbon dioxide (CO₂), into the atmosphere [13]. Consequently, over recent decades, heavy reliance on hydrocarbon resources has made CO₂ the primary gas emitted due to human activities, raising significant concerns about its contribution to global warming [14].

Figure 4 provides an overview of the historical evolution of global CO₂ emissions over the years. This graph shows that emissions began to increase substantially after the advent of the first industrial revolution, highlighting the correlation between industrialization and rising CO₂ levels.

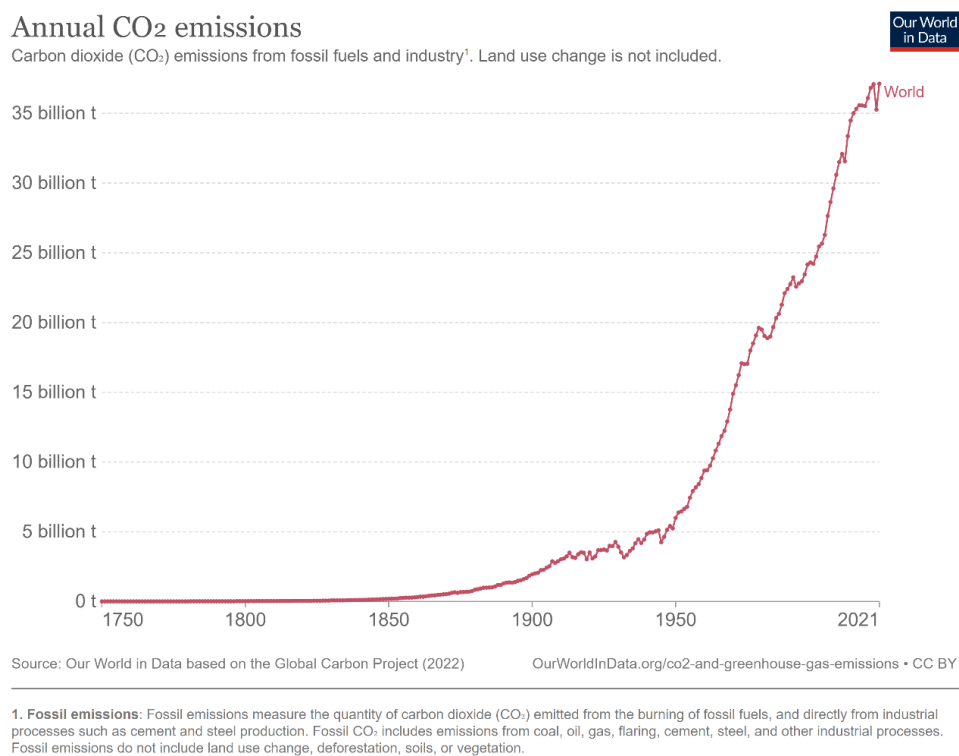


Figure 4 - Evolution of global CO₂ emissions (Source: [15])

According to the National Aeronautics and Space Administration (NASA), the Earth's average temperature has increased by more than 1.2 degrees Celsius since the late 19th century [16]. This temperature rise is primarily attributed to the increase in greenhouse gas emissions, particularly after the conclusion of the second industrial revolution, resulting from the intensive

² According to [159], the greenhouse gases are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). The greenhouse effect happens when certain gases (greenhouse gases) stay trapped in the terrestrial atmosphere. These gases allow the light from the sun to pass but retain the heat that is reflected in the atmosphere, i. e., somehow, they act like a thermal insulator. The greenhouse effect maintains the terrestrial climate stable and comfortable [160].

use of fossil fuels [17]. Figure 5 shows evidence that the intensive use of hydrocarbon resources is directly linked to global warming, primarily due to CO₂ emissions.

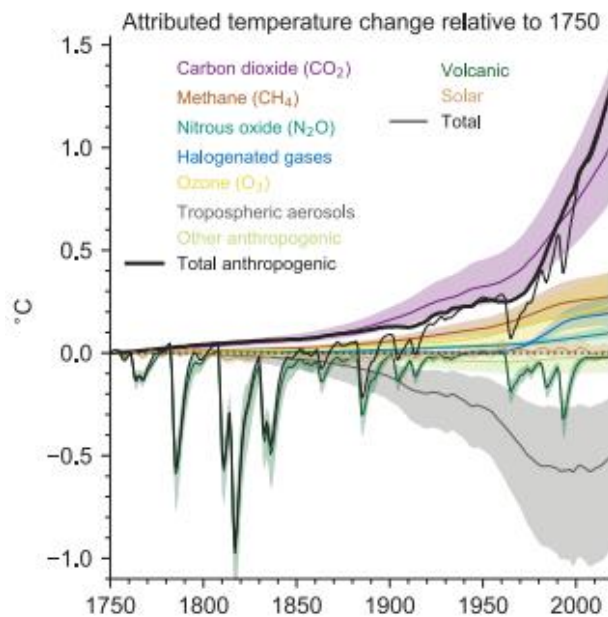


Figure 5 - Relationship between temperature rise and various gases (Source: [14])

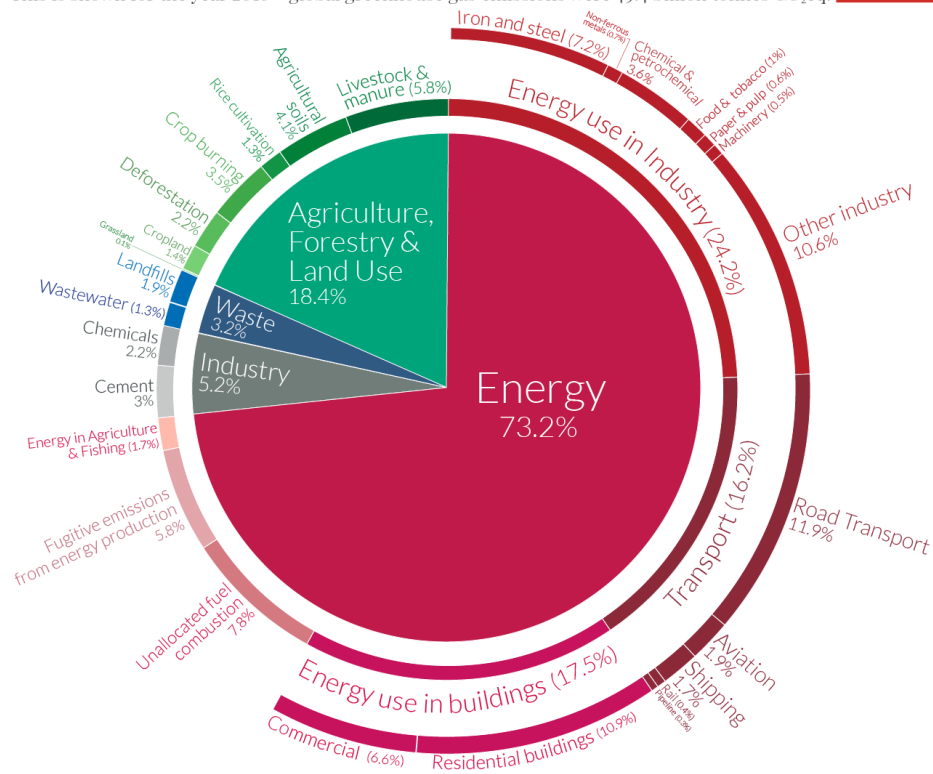
The continuous focus on economic growth (evidenced by the rise of global GDP) and the rapid population expansion led to a notable increase in worldwide energy consumption over the years. Furthermore, despite being geographically limited and challenging to access, fossil fuels constitute over 80% of the world's energy portfolio [18].

Energy generation, transportation, and use appear to be the most significant contributors to the emissions of greenhouse gases. Indeed, in [19], it is argued that approximately 65% of GHG emissions are directly associated with energy generation. In the European Union, this percentage rises to about 77%, according to [20]. According to [21], energy use is responsible for almost three-quarters of the global emissions of greenhouse gases, as illustrated in Figure 6. Moreover, industry, buildings, and transportation sectors stand out in this field.

The authors of [22] state that electricity generation is today's single largest source of energy-related CO₂ emissions. This situation is due to the fact that fossil fuels currently account for 60% of global electricity generation, so a fully decarbonised electric sector is mandatory to combat climate change [23].

Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO₂eq.



OurWorldinData.org – Research and data to make progress against the world's largest problems. Source: Climate Watch, the World Resources Institute (2020). Licensed under CC-BY by the author Hannah Ritchie (2020).

Figure 6 - GHG emissions by sector (Source: [21])

The availability of fossil fuels has decreased over the years, approaching shallow levels [24]. Furthermore, the price of a barrel of oil has surged to historic highs in global markets [25], and the prevailing trend suggests this value will persist in its upward trajectory in the coming decades [26]. Despite this, fossil energy consumption continues to increase yearly, consequently increasing greenhouse gas emissions.

Therefore, global warming due to greenhouse gas emissions tends to make itself feel more and more. As a result, extreme weather events tend to be more frequent and severe, including floods, droughts, wildfires, storms, and sea-level rise [27], [28]. Apart from climate impacts, another substantial consequence of air pollution, and potentially even more critical, is its impact on human health. Indeed, air pollution originated from the use of fossil fuels may cause several health issues (including an elevated risk of cancer, cardiovascular diseases, and respiratory ailments [29]) and many premature deaths [30], [31].

To address this urgent concern, the 2015 Paris Agreement was crafted to foster global collaboration in combating climate change. Its objectives include limiting global warming, reducing greenhouse gas emissions, supporting adaptation measures, providing financial

assistance, and ensuring transparency and accountability [32], [33]. The Paris Agreement underscores the imperative for humanity to take various actions to mitigate the consequences of climate change.

This work, developed under the research project “Sustainable Transformative Transitions - reconcile the acceleration of low carbon transitions with system transformations” - (PTDC/GES-AMB/0934/2020) – work package 2, funded by the Foundation for Science and Technology, focuses on the decarbonisation theme. The work seeks to contribute to identifying and assessing decarbonisation technologies and strategies, accounting for aspects such as readiness, potential and risk. Moreover, the work aims to forecast the expected avoided CO₂ emissions for the Portuguese power system until 2050.

1.2. Objectives

The present dissertation was developed in the scope of the project titled “*Sustainable Transformative Transitions - Reconciling the Acceleration of Low Carbon Transitions with System Transformations (SUS2Trans) - PTDC/GES-AMB/0934/2020.*” This project primarily investigates decarbonisation strategies that align with the Paris Agreement, whose implementation requires the transformation of various sectors, including energy, mobility, construction, food, and industry. The project’s expected outcomes include the development of a typology of transformative decarbonisation strategies and examining emerging patterns of transformation towards more sustainable modes of production and consumption. The findings are to be compared with decarbonisation strategies derived from scientific literature, contributing to the ongoing discussion about sustainable transition processes and forms associated with the economic characteristics of different regions.

More specifically, this dissertation’s first set of objectives closely aligns with the goals outlined in Work Package 2 (WP2) of the *Sus2Trans* project. Therefore, the fundamental objectives of the work included:

- identifying domains of disruptive technological innovations with the potential to support decarbonisation;
- characterising the identified domains of technologies regarding: i) the importance attributed to them by the scientific community; ii) the state of maturity; iii) the potential for mitigating emissions;

- the intersection of identified domains of technologies with a set of pathways to decarbonisation defined in the Work Package 1 of the *Sus2Trans* project and the subsequent characterisation of those pathways concerning: i) the readiness level; ii) the potential for decarbonisation; iii) and the technological risk.

The second set of objectives aimed to develop and implement a comprehensive methodology for evaluating the progression of emissions in the Portuguese electrical system until 2050. This methodology should encompass the following aspects:

- consider different scenarios of non-conventional renewable-based power generation evolution;
- account for various scenarios of electricity consumption development;
- incorporate the potential impact of electric mobility, including different electric vehicle charging patterns;
- evaluate the potential effects of energy storage on emissions reduction;
- assess the influence of the distribution of non-conventional generation and storage system capacities across power system networks on emissions reduction.

1.3. Dissertation structure

This dissertation is organized into six chapters, including this one, which serves as an introduction to the framework of the work, the presentation of objectives, and an overview of the document's structure. Furthermore, a scientific publication conducted as part of the research is also included in this chapter.

Chapter 2 focuses on identifying the domains of innovative technologies prevalent in the existing literature (scientific, research projects and patents) to support decarbonisation. A comprehensive bibliometric analysis is conducted to determine the level of interest in each domain of technologies within the scientific community.

Chapter 3 assesses the maturity of innovative technologies associated with decarbonisation and the domains identified in Chapter 2. The maturity of the defined domains of technologies is also assessed. Additionally, this Chapter evaluates the maturity, risk, and potential for emissions mitigation of different literature-based decarbonisation pathways derived elsewhere.

Chapter 4 introduces a model devoted to estimating the potential evolution of avoided emissions of a generic electrical power system over the years. Among other aspects, the model accounts for various scenarios of power generation and consumption, the potential impact of electric mobility, and the influence of the integration of storage systems.

The model developed in Chapter 4 is applied in Chapter 5, focusing specifically on the Portuguese electrical system. A comprehensive preliminary assessment of the electric Portuguese system was conducted to achieve this. Forecasts are presented regarding the growth of non-conventional generation and electricity consumption on the grid. Therefore, a range of scenarios is defined. These scenarios also incorporate the potential influence of electric mobility on electricity consumption patterns. To properly apply the model, various assumptions are made. These encompass pertinent details such as typical electricity generation and consumption profiles and factors related to losses and emissions. The model is effectively employed, and several analyses are conducted to predict the progression of emissions from the electrical system, particularly in avoided emissions. Moreover, sensitivity analyses are performed to evaluate the impact of certain factors, such as the distribution of storage systems and non-conventional generation within the electrical networks, on reducing emissions.

Finally, Chapter 6 will expose the conclusions of the works as well as future work prospects.

1.4. Publication

A scientific paper entitled “*Identifying Promising Domains of Decarbonization Technologies: An Improved Methodology*” was published as part of this work. This publication took place within the scope of the *8th International Conference on Smart and Sustainable Technologies (SpliTech)*, 2023.

The Proceedings of the *SpliTech* conference are indexed by *IEEE Xplore*®, as seen in Figure 7.

Conferences > 2023 8th International Confer... Back to Results | Next >

Identifying Promising Domains of Decarbonization Technologies: An Improved Methodology

Publisher: IEEE Cite This PDF

Paulo Moisés Costa ; Paulo Tomé ; António Duarte ; Nuno Bento ; Bruno Almeida All Authors

42

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Abstract

Document Sections

I. Introduction

Abstract:

Humanity has sought ways to decarbonize the economies and mitigate the effects of global warming. The scientific community has been producing intensive research on decarbonizing technologies and strategies. This article introduces an improved methodology, based on two available text-mining software, to identify the most relevant domains of decarbonizing

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Published: 2021

Figure 7 - Article published and indexed in IEEE Xplore® (Source: [34])

2. IDENTIFICATION OF DECARBONISATION TECHNOLOGY DOMAINS

This chapter provides an overview of the work conducted to identify the domains of innovative decarbonisation technologies and instruments that have received significant attention from the scientific community in recent years. A methodology based on two text-mining tools was developed and applied to achieve this objective. Documents from databases of scientific publications (Scopus and Web of Science), research projects (Cordis), and patents (Patstat) were examined. Computational software was developed and used to process the outputs of the text-mining software and obtain a relevant set of terms related to decarbonisation technologies/instruments.

2.1. Related works

In the scientific literature, some studies utilize text-mining software to track and analyze decarbonization technologies and policies, efficiently extracting valuable insights and trends from vast data.

Reza et al. [35] searched the Scopus database for publications on energy storage and decarbonization indexed between 2011 and 2021. The authors conclude that integrating storage systems into grids can be essential in decarbonizing the electricity sector. Indeed, when associated with the integration of renewable energies, the storage systems allow for the replacement of conventional fuels used in electricity generation and provide the necessary flexibility to face problems related to the dependence of renewable generation on weather conditions.

The impact of the diffusion of energy efficiency technologies on decarbonization in European residential buildings is assessed in [36]. The authors use text-mining software to explore the Web of Science (WoS) database for 2008-2018. They concluded that an asymmetrical research activity exists in Europe since certain member states show an active research activity and others have little or no publications. They also conclude that, although energy efficiency has seen exponential growth in the number of publications, more research is needed to quantify and monetize its impacts.

A bibliometric perspective on research on carbon capture, storage and use (CCSU) in China is done in [37]. The Citespace software is used to map the information of 1202 scientific documents taken from the WoS database concerning the research focuses, most productive organizations and principal authors for 2002-2019. The authors point out that establishing government policies around CCSU influenced the trend of research in China.

The authors in [38] use the Visualisation of Similarities viewer (VOSviewer) software, a free tool, to perform a bibliometric analysis of research trends around green Hydrogen (H₂), analyzing the publications extracted from the Scopus database for the 2016 to 2021 period. The authors highlight the number of articles published in the adopted period, the most productive organizations and countries, and the most relevant research items about green H₂.

A revision of the literature about the main concepts related to climate change mitigation and its progress over time is presented in [39]. The authors use the Scopus database to obtain the scientific content and the VOSviewer software to analyze it, extract conclusions about the geographic and sectoral focus, and determine the interrelationships between the key concepts. This study stands out from the others for studying decarbonization in general and not a specific technology or sector, even though it uses only one scientific database and one text-mining software.

CiteSpace software is used in [40] to conduct a bibliometric analysis of developments in low-carbon energy generation. The research is based on 1419 articles from 1983 to 2021, retrieved by the Scopus database. The authors concluded that the number of publications has increased over time and that China and the United States lead publications on this topic. They also conclude that renewable energy resources and storage are crucial for decarbonizing.

At [41], the Science Citation Index Expanded and Social Sciences Citation Index databases are used to gather the literature on the decarbonization of the electricity system on a global scale. Using a quantitative analysis of article titles, abstracts and keywords, the authors conclude that dependence on coal and nuclear fuels in the 1990s stimulated the search for cleaner alternatives, resulting in more publications on Carbon Capture and Storage and wind energy in the first decade of the 21st century. Furthermore, the authors conclude that the constant focus on energy efficiency will continue.

The literature review evidences that the existing research mainly evaluates separate technologies and utilises a single text-mining tool. Furthermore, the bibliometric analyses largely depend on scientific publications databases, neglecting sources such as patents and

research project databases. The few studies that do compare different technological progressions also do not specify the technology domains that offer the most significant potential for decarbonization.

Therefore, in the following section, two text-mining software tools are used to identify the domains of innovative decarbonisation technologies and instruments that have received significant attention from the scientific community in recent years. Concretely, the *Tools for Innovation Monitoring* (TIM) [42] and the *VOSviewer* from Leiden University [43] software are used to identify technological trends in literature, projects, and patents. The recognised innovative decarbonisation technologies and instruments were then used as the basis for the definition of technology domains.

2.2. Methodology

2.2.1. Approach

The selection of relevant scientific information can be complex due to the massive number of publications, patents and research projects available about decarbonization technologies and strategies. For this reason, the software tools devoted to bibliometric analysis may be a helpful resource for finding more relevant information.

As previously stated, two text-mining software tools are used in this work to identify the domains of innovative decarbonisation technologies and instruments that have received significant attention from the scientific community in recent years: the TIM and the VOSviewer.

VOSviewer is a software tool that facilitates diverse forms of bibliometric analysis. This software enables insightful exploration of various types of connections, such as co-authorship, co-occurrence, citation, bibliographic coupling, and co-citation. Users can choose from three visual representations: network, overlay, or density visualization. In this work, the analysis carried out specifically used documents sourced from the Web of Science (WoS) database, acquired through a dedicated search engine. The set of acquired documents served as the input for VOSviewer, which was used to extract the desired information, consisting of the author keywords and their respective “occurrence”. It is important to note that the term “occurrence” means the frequency of appearance of a particular keyword in the documents.

The TIM software analyses and tracks various established and emerging technologies. It retrieves bibliometric data from databases like SCOPUS, CORDIS, and PATSTAT. Unlike VOSviewer, TIM automatically obtains the dataset of documents to be analyzed, eliminating the need for manual extraction. The search can be conducted in different fields, such as papers, projects, and patents. In this study, the investigation focused on the documents' titles, abstracts, and keywords in the source databases. Once the dataset is obtained, TIM uses different algorithms to classify the keywords. In this study, the “Relevant Keywords” algorithm was chosen. This algorithm ranks keywords based on their “relevance” value, which is determined by a modified version of the classic Inverse Document Frequency (TF-IDF). TF-IDF assigns different weights to keywords based on their location within the document: 1 for the title, 0.5 for the abstract, and 2 for the keyword field. It’s worth noting that the “relevance” obtained through the TIM tool should not be directly compared to the “occurrence” obtained using VOSviewer, as they measure different aspects of the data.

A more detailed description of the TIM and VOSviewer software may be found in APPENDIX A.

Figure 8 summarizes the methodology adopted for identifying the domains of technologies for decarbonisation. The proposed methodology can be summarized in three main steps. The first step involves gathering a comprehensive collection of raw terms from relevant scientific documents sourced from suitable databases. In the second step, the extracted terms will go through a normalization, filtering, and aggregation process to streamline the data for further analysis. This procedure ensures the terms are organized and consistent, providing a solid foundation for subsequent analysis. Lastly, in the third step, the technology domains prevalent in the scientific literature are identified by analyzing the aggregated data, patterns, and trends.

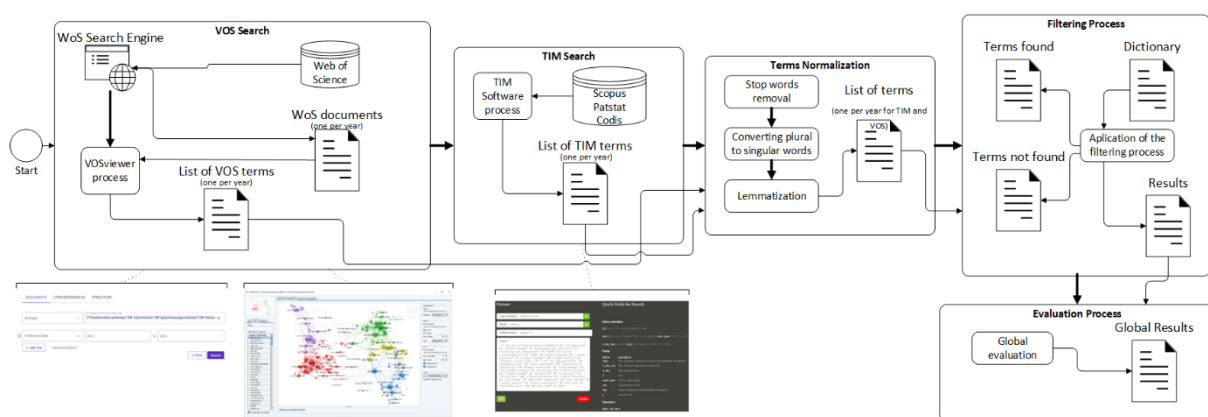


Figure 8 - Methodology for bibliometric analysis

2.2.2. Obtention of raw terms

2.2.2.1. Search string construction

The list of raw terms was obtained from a bibliometric analysis using the TIM and the VOSviewer software. However, getting a set of relevant documents on which such analysis will focus was necessary before carrying out the bibliometric analysis. As previously mentioned, in this work, these documents were obtained from databases of scientific publications (WoS, Scopus), research projects (Cordis) and patents (Patsat).

The obtention of the documents required the definition of a boolean search string used in the TIM and WoS search engines. This search string was developed using a previous literature review on decarbonization technologies, which helped determine relevant decarbonization terms. Table 1 shows the terms about decarbonisation that resulted from the literature review.

Table 1 - Terms related to decarbonization resulting from the literature review

Transformation pathways	CO ₂ emission	Greenhouse emission gas	Carbon dioxide
Technological innovations	2050	System transformation	2030
Global warming	Climate solution	Climate target	Climate policy
Displace fossil fuels	1.5°	GHG emission	Greenhouse gas
Paris Agreement	Transition in electricity	Energy transition	Clean energy
Sustainable energy	New energy	Carbon emission	Climate change
Mitigation	Technology	Disruptive	Decarbonization
Carbon reduction	Low carbon	Emission reduction	Zero carbon
Carbon neutral	Carbon Neutrality	Net-zero	Decarbonised

Additionally, the search string was designed to accommodate the specific features of the WoS and TIM search engines (e.g., considering words in plural or singular is automatic in TIM but not in WoS). Furthermore, the logical operators “AND” and “OR” were used to link the adopted terms.

The obtained search string, which was used in the search engines of TIM and WoS, was the following:

((“transformation pathway” OR “co2 emission*” OR “carbon dioxide” OR “greenhouse gas emission*” OR “technological innovation*” OR “2050” OR “system transformation*” OR “2030” OR “global warming” OR “climate solution*” OR “climate target*” OR “climate policy” OR “displace fossil fuels” OR “1.5°” OR “ghg emission*” OR “greenhouse gas” OR “paris agreement” OR “transition in electricity” OR “energy transition” OR “clean energy” OR “sustainable energy” OR “new energy” OR “carbon emission*” OR “climate change” OR “mitigation” OR “technology” OR “disruptive”) AND (“decarbonisation” OR “carbon reduction” OR “low carbon” OR “emission* reduction” OR “zero carbon” OR “carbon neutral” OR “carbon neutrality” OR “net-zero” OR “decarbonised”))*

Note that the search string consists of two parts connected by a logical AND operator. This ensures that each document retrieved from the databases contains at least one term from both parts of the string. This design aims to capture the most pertinent technology domains for decarbonization while reducing the retrieval of irrelevant data and staying within the 10,000 document limit imposed by the TIM software.

2.2.2.2. Documents obtention

The search string defined in the previous section was used with the WoS and TIM search engines to obtain the pertinent documents (the ones that fit the search string) for each year from 2011 to 2021. The documents were collected by year, enabling temporal progression analysis.

In the case of TIM, two filters, as seen in Figure 9, were adopted together in the search string: i) the “ti_abs_key” that seeks to find terms in the “title”, “abstract”, and “author’s keyword field” of the documents; ii) and the “emm_year” which limits the search to a specific period [44].

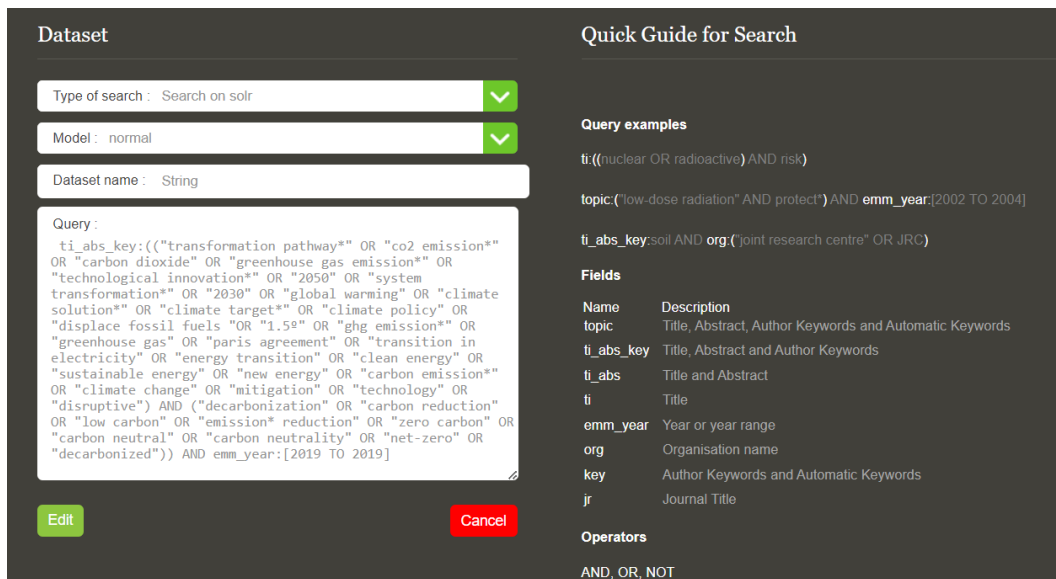


Figure 9 - Search in TIM

In the case of the WoS search engine, the filters mentioned are parameters that can be selected while searching. These filters do not require inclusion in the search query string itself, as shown in Figure 10. This work performed the search with the “topic” parameter, which retrieves documents by searching within the following fields: titles and abstracts, author keywords and keywords plus. The keywords plus are created through an algorithm that generates keywords based on cited references. Additionally, the desired time period for the search can be specified using the “publication date” field parameter [45].

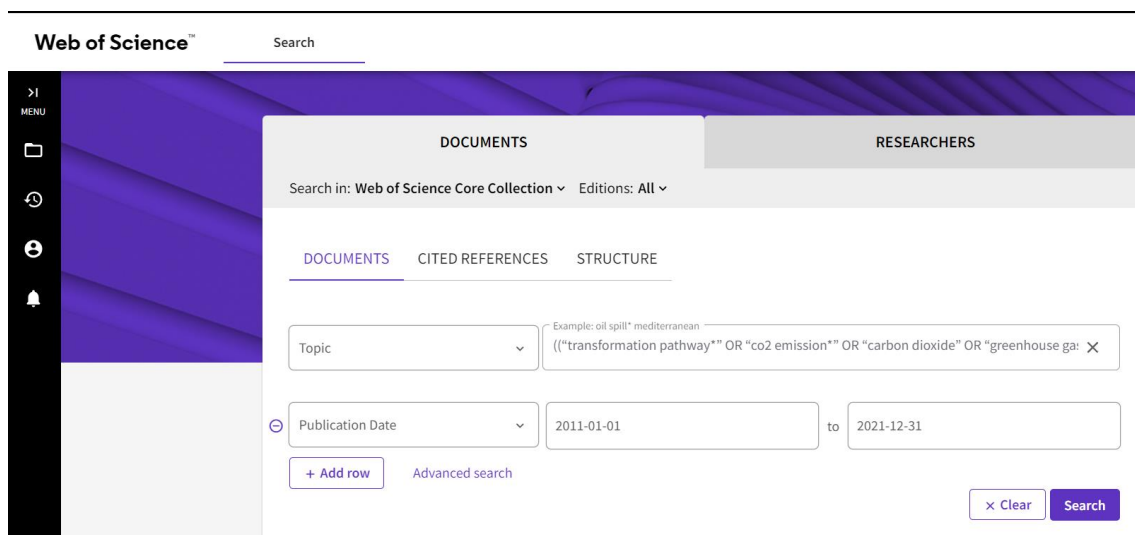


Figure 10 - Search in WoS

Figure 11 and Figure 12 show extracts of the sets of documents obtained using the defined *research string* in WoS and TIM, respectively.

Search > Results for ("Transformation pathways" OR "co2 emission" OR "greenhouse...)

19,443 results from Web of Science Core Collection for:

Q ("Transformation pathways" OR "co2 emission" OR "greenhouse gas emission" OR "technological innovations" OR "2050" OR "System tran...)

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1 A systematic bibliometric review of **clean energy** transition: Implications for **low-carbon** development

Zhang, W.; Li, B.S.; (-); Cao, W

Dec 3 2021 | PLOS ONE 16 (12)

8 Citations
119 References

More voices are calling for a quicker transition towards **clean energy**. The exploration and exploitation of **clean energy** such as wind energy and solar energy are effective means to optimise energy structure and improve energy efficiency. To provide in-depth understanding of **clean energy** transition, this paper utilises a combination of multiple bibliometric mapping techniques, including HistCite, ... Show more

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2 DETERMINANTS OF THE **ENERGY TRANSITION**: EMPIRICAL EVIDENCE FOR OECD COUNTRIES

Alfonso, J.L.; Marques, A.C. and Fuinhas, J.A

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10 References

The **energy transition** is a requirement to accomplish the objectives of the international agreements. Since the Kyoto protocol that countries increased the share of renewable energy by replacing fossil sources. The concept of **energy transition** depends on the nuclear role in the **energy transition**. Consider different types of **energy transition**, this paper analyses the determinants of the low carbon ... Show more

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Figure 11 - Extract from the documents retrieved by WoS

Validate dataset

Dataset definition : ti_abs_key:(("Transformation pathways" OR "co2 emission" OR "greenhouse gas emission" OR "technological innovations" OR "2050" OR "System transformation" OR "2030" OR "global warming" OR "climate solution" OR "climate target" OR "climate policy" OR "displace fossil fuels" OR "1.5°" OR "ghg emission" OR "green house gas" OR "Paris Agreement" OR "transition in electricity" OR "energy transition" OR "clean energy" OR "sustainable energy" OR "new energy" OR "carbon emission" OR "climate change" OR "mitigation" OR "technology" OR "disruptive") AND ("decarbonization" OR "carbon reduction" OR "low carbon" OR "emission reduction" OR "zero carbon" OR "decarbonised") AND emm_year:[2018 TO 2018])

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Figure 12 - Extract from the dataset retrieved by TIM for the year 2018

A total of 87,212 documents were recovered, 59,411 from TIM and 27,801 from WoS databases. Figure 13 shows the number of documents retrieved each year, allowing us to perceive, in the TIM case, the number of documents related to scientific papers, patents and research projects.

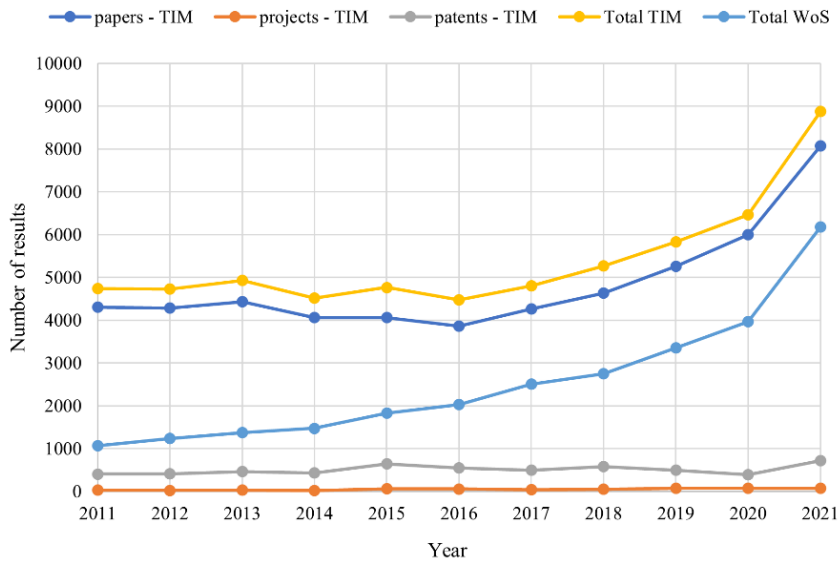


Figure 13 - Number of documents retrieved by TIM and WoS

2.2.2.3. Bibliometric analysis

The documents obtained from the databases using the procedure described in the previous sections were then utilized as input for the text-mining software. Therefore, the TIM and the VOSviewer software conducted a bibliometric analysis based on the documents obtained under the above-explained conditions. A detailed description of how TIM and VOSviewer are used to perform bibliometric analysis can be found in APPENDIX A.

In the case of VOSviewer software, the bibliometric analysis retrieved the “Author Keywords” and their respective “occurrence” extracted from the considered documents. Figure 14 shows an extract of such information.

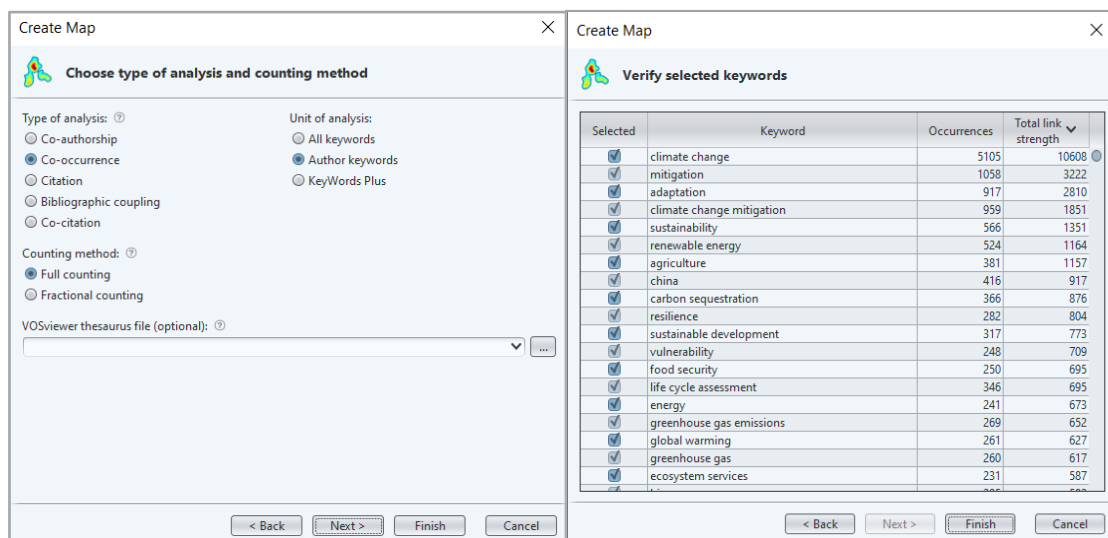


Figure 14 - Obtention of keywords and their occurrence in VOS software

On the other hand, the bibliometric analysis done by the TIM software retrieved the “Relevant Keywords” of the considered documents with their corresponding relevance value. Note that the “Relevant Keywords” are obtained from the processed document’s titles, abstracts, and keywords. An extract of such information may be found in Figure 15.

The screenshot shows a table with two columns: 'Keyword' and 'Relevance'. The table is titled 'Entries: 93249'. The keywords listed are: climate change (CC), co2 emission (CE), ghg emissions, greenhouse gas emissio..., green house gas (GHG), mitigating climate change, greenhouse gas, fossil fuel (FF), carbon capture storage (...), carbon emission (CE), global warming (GW), low carbon (LC), and mitigation and adaptation. The relevance values range from 237 to 80.

Keyword	Relevance
climate change (CC)	237
co2 emission (CE)	231
ghg emissions	204
greenhouse gas emissio...	169
green house gas (GHG)	159
mitigating climate change	128
greenhouse gas	88
fossil fuel (FF)	88
carbon capture storage (...)	87
carbon emission (CE)	82
global warming (GW)	82
low carbon (LC)	82
mitigation and adaptation	80

Figure 15 - Obtention of keywords and their relevance in TIM software

Note that each “Author Keyword” or “Relevant Keyword” may encompass two or more words. Therefore, from now on, the “Author Keyword” and the “Relevant Keyword” will be referred to as terms.

The bibliometric analyses were carried out annually to assess the evolution of the scientific community’s interest in decarbonization technologies throughout the study period (2011-2021). Therefore, the bibliometric analysis done by TIM and VOSviewer software retrieved 11 sets (one per year) of “Relevant Keywords” and their “relevance” (TIM) and another 11 sets of “Author Keywords” and their “occurrence” (VOSviewer). Figure 16 shows the keywords retrieved by each text-mining software for each year of the considered study period. A total of 793,700 keywords (689,075 from TIM and 104,625 from VOSviewer) were obtained.

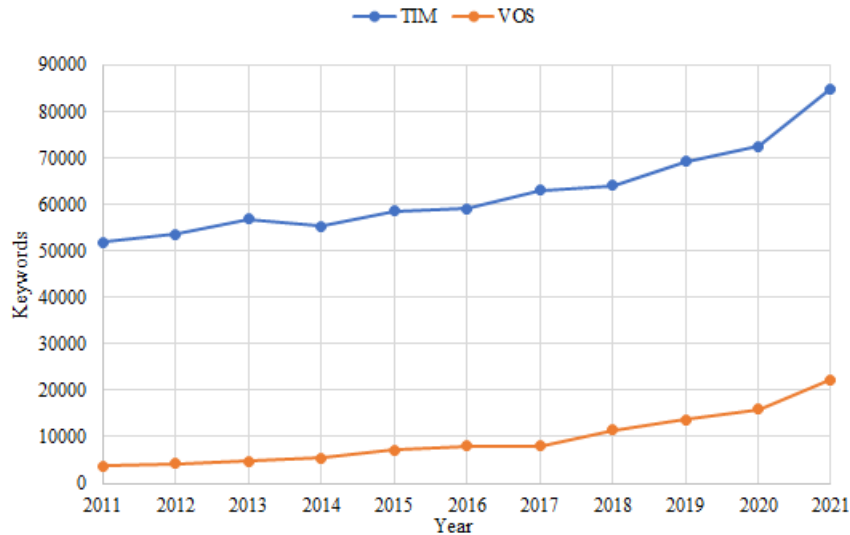


Figure 16 - Number of keywords retrieved from TIM and VOSviewer

2.2.3. Obtention of final terms

Since the bibliometric analysis was conducted yearly, multiple repetitions of terms occur, imposing the need for their remotion. Therefore, basic Excel functions were used with the lists of terms to eliminate the repeated terms, dispensing the need for any specific computational tool.

After repeated terms were eliminated, 196,129 terms remained (155,778 from TIM and 40,351 from VOSviewer). However, the final number of non-repeated terms equals 176,029, since there were also some repeated terms in the sets retrieved by TIM and VOSviewer.

However, the list of terms (without the repeated terms) included numerous terms that do not pertain to the intended study and must be eliminated. For instance, the term “climate change” appears in the terms retrieved by TIM software, as seen in Figure 15. However, this term is not appropriate for the context of the study because it does not refer to decarbonisation technology. Moreover, different terms with the same meaning (such as PV system, photovoltaic, photovoltaics, solar PV, etc.) are present and should be combined in the same group.

Consequently, it was essential to process the list of raw terms by eliminating irrelevant entries and aggregating the various versions of the same meaning. However, before this important task, the obtained sets of terms were subjected to a normalisation procedure to

consolidate the retrieved list of raw terms [46]. A python code was implemented for this purpose. This code allowed for returning plural nouns to the singular form, returning inflected verb forms to their stem, returning comparative adjectives to their primary form, and eliminating connectors and stop words. Unnecessary acronyms/abbreviations have also been eliminated. However, once not all acronyms/abbreviations can be removed (e.g. the H₂ in the term “H₂ storage”), a procedure has been implemented to avoid such situations by replacing the acronym/abbreviation with the text it represents. Table 2 shows some adjustments resulting from the normalisation procedure.

Table 2 - Examples of normalised terms

Initial term	Normalised term
co2	carbon dioxide
photovoltaics	photovoltaic
green ammonia	green ammonium
battery technologies	battery technology
co2 flux	carbon dioxide flux
renewable fuels	renewable fuel
energy and building	energy building

The lists of normalised terms were then used as the input for a filtering procedure implemented through a python-based program. This program employed a customized semantic dictionary to eliminate irrelevant terms and merge terms with similar meanings. For example, terms such as “low carbon” and “carbon emissions” were filtered out, while terms like “photovoltaic system”, “photovoltaic”, and “solar photovoltaic” were merged due to their identical meanings. Therefore, the semantic dictionary is a crucial component of the filtering process.

Figure 17 shows the procedure adopted for constructing the semantic dictionary. This construction started with defining an initial set of 102 terms related to technologies for decarbonisation. This initial dictionary was based on a preliminary bibliographical review and considering the retrieved datasets by TIM and VOSviewer. An iterative semi-automatic approach [47] was then adopted to complement the dictionary. This iterative procedure is intended to contribute to the dictionary’s robustness, leading to increased confidence in the effectiveness of the entire filtering.

The automatic part of the procedure was implemented using a Python code program developed for this purpose. The Levenshtein approach [46], which measures the differences between two text strings, was adopted to generate new terms for each dictionary entry. In

practice, the developed program compares the existing terms in the current dictionary to those in a list containing terms retrieved by TIM and VOSviewer (the processed terms). According to the defined degree of similarity, some terms are automatically included in the current dictionary.

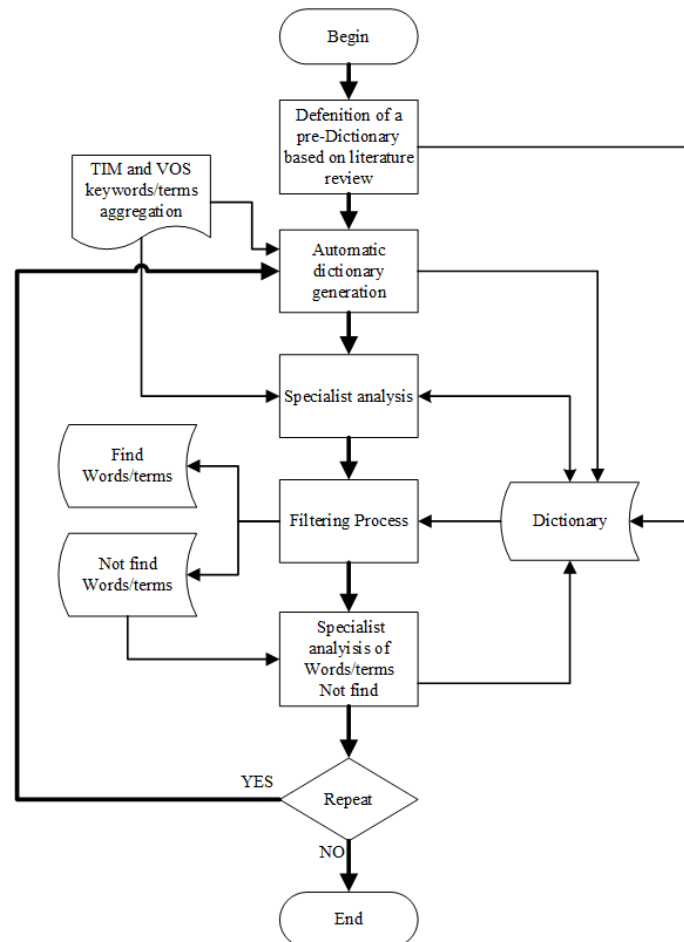


Figure 17 - Procedure to create the semantic dictionary

Afterwards, the terms included in the dictionary were checked to decide which ones should be retained in the updated version. As a result, some terms that were included in the dictionary through the automatic procedure were removed in this step.

In the next step, a filtering process is used to update the list containing the terms retrieved by TIM and VOSviewer (the list of normalized terms). This filtering process enables the identification of terms not found in the current semantic dictionary version nor in the set of words eliminated from the dictionary during the specialist evaluation phase. A python code was implemented to compare each term in the current list containing the terms retrieved by TIM and VOSviewer with the terms already included in the dictionary and with the list of words eliminated from the dictionary during the specialist evaluation phase. Therefore, the program

created two lists of terms: the list of found terms and the list of not-found terms. The list of non-found terms will be assumed to be the new (updated) list of terms retrieved by TIM and VOSviewer. This list was then used in the next iteration of the procedure to construct the semantic dictionary (in the automatic step). Figure 18 schematically shows how the filtering process works.

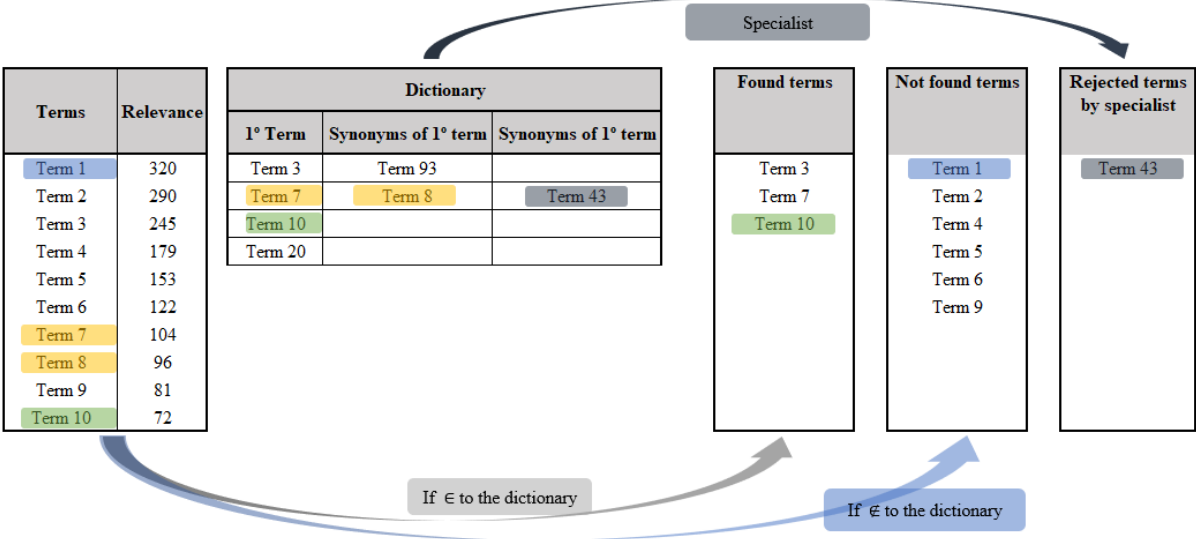


Figure 18 - Filtering process for the dictionary

In the last step of the procedure depicted in Figure 17, the specialist examines the list of non-found terms and can manually include specific terms from this list into the semantic dictionary. This inclusion accelerates the iterative process described in Figure 17, resulting in faster convergence.

The steps above are repeated until a specific convergence criterion is reached, achieving a final version of the semantic dictionary.

The described procedure was applied with the set of raw terms after eliminating repeated terms and the normalization procedure. A total of 12 iterations were done, as shown in Figure 19, which also evidences the evolution of the number of terms in the dictionary.

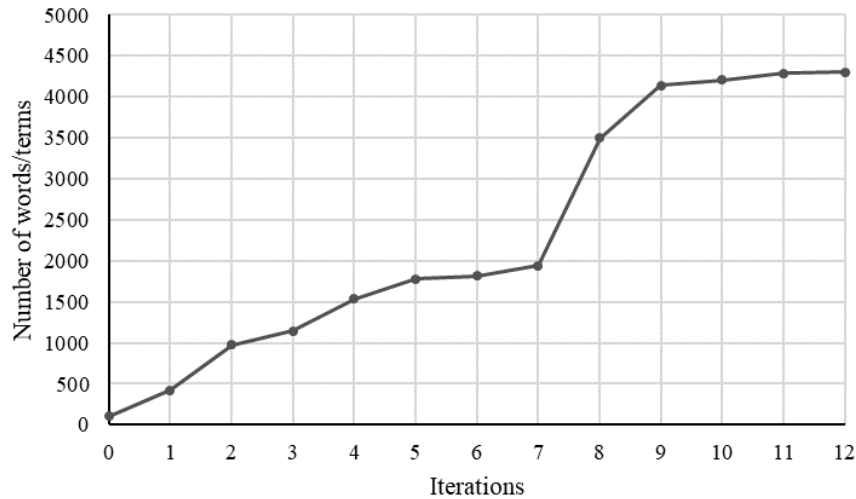


Figure 19 - Evolution of the making of the semantic dictionary

Note that the first seven iterations used only the terms retrieved by TIM and VOSviewer for 2020 and 2021. On such iterations, the Levenshtein ratio started with a value of 0.75 and was increased along the iterative procedure until the maximum value of 0.9 (steps of 0.05 were used). The last five iterations accounted for all the terms (176,029) retrieved by TIM and VOSviewer for the study period (2011-2021). This fact justifies the drastic increase of terms in the dictionary from iterations 7 to 8. The Levenshtein ratio was redefined in the eighth iteration as equal to 0.8 and increased by 0.05 on the subsequent iterations until it reached the value of 0.9.

The iteration process stopped when the list of terms not found, obtained from the filtering process, did not include any terms that met the criteria of having an occurrence greater than three or a relevance greater than five to be added to the dictionary.

The final dictionary has 4300 terms divided by 426 sets with similar semantic meanings. Figure 20 shows an extract of the obtained semantic dictionary. Note that this version of the semantic dictionary contains the set of final terms.

1	renewable energy system	renewable energy	hybrid renewable energy system	...
4	photovoltaic	photovoltaic energy	photovoltaic panel	...
13	perovskite solar cell	perovskite silicon tandem solar cell	perovskite	...
16	solar chimney power plant	solar chimney	hybrid solar chimney power plant	...
22	photovoltaic thermal	building photovoltaic thermal	photovoltaic thermal collector	...
28	building integration solar based tec	solar thermal integration	solar energy integration	...
38	ocean	ocean energy	ocean renewable energy	...
55	biomethane	biochemical methane potential	biomethanation	...
69	biomass	crop production	wood production	...
104	nuclear fission	fission power system	fission energy	...
115	renewable hydrogen production	sustainable hydrogen production	biohydrogen	...
139	hydrogen turbine	hydrogen engine	hydrogen internal combustion engine	...
162	electricity transmission	inter regional power transmission	interprovincial electricity transmission	...
175	air source heat pump	air heat pump	air water heat pump	...
...

Figure 20 - Extract of the semantic dictionary

2.2.4. Technology domains

2.2.4.1. Definition of technology domains

The semantic dictionary introduced previously served as the foundation for delineating the domains of innovative decarbonisation technologies. Indeed, this dictionary played a crucial role in a filtering process similar to the one described in section 2.2.3. However, in this instance, the filtering process was solely employed to consolidate related terms and calculate the aggregated values of relevance and occurrence, as depicted in Figure 21. Note that term 20 exists in the final list in the given example, even though it is not in the list of terms currently being processed. Therefore, it appears in the final list with a relevance value of zero. The reason for its inclusion in the result is that even though it has a relevance value of zero, term 20 may still have a non-zero occurrence. The filtering process was conducted annually and independently for the terms obtained through TIM and VOSviewer. Thus, 11 sets (1 for each year of the study period) of 426 technologies/instruments for decarbonization and the respective aggregated relevance were obtained after the filtering process. Likewise, 11 sets of technologies/instruments and their respective aggregate occurrence were defined.

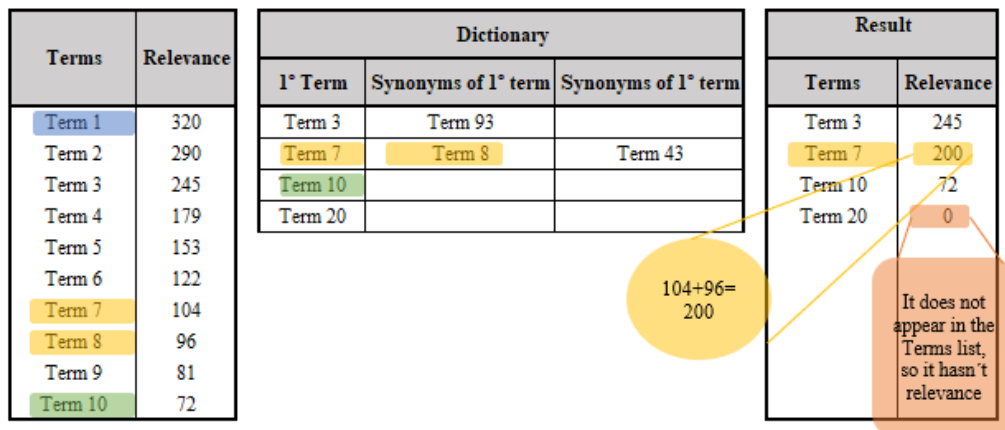


Figure 21 - Filtering process that supported the definition of the domains

After the filtering process, the 426 groups of technologies/instruments were aggregated into domains of technologies. The aggregation considered the similarities and patterns among similar sets of technologies/instruments. For example, a domain called “photovoltaic” was created, which included two sets of technologies/instruments: “photovoltaic” and “perovskite solar cell”. Another example is the domain designated by “marine energy”, which includes three sets of technologies/instruments: “wave and tidal energy”, “thermal energy conversion”, and “non-specified marine energy”. Note that the values of “relevance” and “occurrence” from the

sets of technologies/instruments included in a specific domain were summed and assigned to the defined domain.

Therefore, the previous 426 technologies/domains were aggregated into 41 domains, as shown in Table 3. It is important to highlight that two defined domains do not fit into the logic of conventional technology domains: “policy and circular measures” and “natural carbon capture and storage”.

Table 3 - Domains

#	Domain	#	Domain
1	not specified renewable	22	energy transmission infrastructure
2	photovoltaic	23	transportation infrastructure
3	solar power/steam generation	24	electrification
4	wind energy	25	heat pump
5	geothermal energy	26	HVAC
6	marine energy	27	microgeneration/selfconsumption
7	hydro power	28	building construction/isolation
8	solar thermal energy	29	low carbon and autonomous transportation
9	combined photovoltaic/thermal generation	30	generic industry furnace/heating
10	not specified distributed generation	31	cement industry
11	hybrid generation system	32	steel, iron and aluminium industry
12	other generation	33	other heavy industry
13	biofuel	34	agricultural sector
14	synthetic fuel	35	energy efficiency and management
15	not specified alternative fuel	36	energy community
16	nuclear power	37	energy storage
17	clean coal/natural gas power plant	38	carbon capture, storage and use
18	natural gas power generation	39	natural carbon capture and storage
19	shale natural gas	40	digitalization and smart systems
20	combined heat/cool/power generation	41	policy and circular measures
21	hydrogen		

2.2.4.1. Assessment of relevance and occurrence

The domains defined in the previous section have not received the same attention from the scientific community. Additionally, the attention received by a specific domain may vary over the years. The attention received by the different domains can be quantified using the concepts of relevance and occurrence explained above.

Figure 22 and Figure 23 show the per-year relevance/occurrence for the 20 technology domains with higher values on those parameters. Note that the “policy and circular measures” and “natural carbon capture and storage” domains are not aligned with the logic of the technology domains. Consequently, they have been excluded from this and the subsequent analysis.

It is important to highlight that the most relevant domains are not necessarily the most common, which makes a direct analysis of the relative positioning between domains difficult. As previously explained, the relevance value retrieved by TIM software should not be directly compared with the occurrence value obtained in the VOSviewer software. Therefore, an approach based on ranking the results from TIM and VOS was adopted in this work. Indeed, a two-step ranking procedure is adopted.

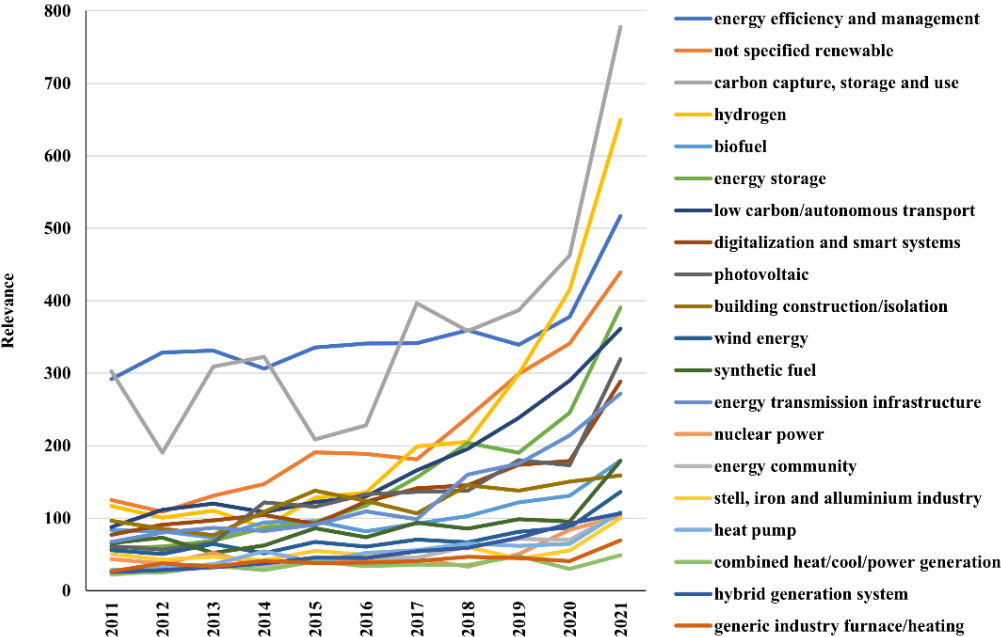


Figure 22 - Relevance values

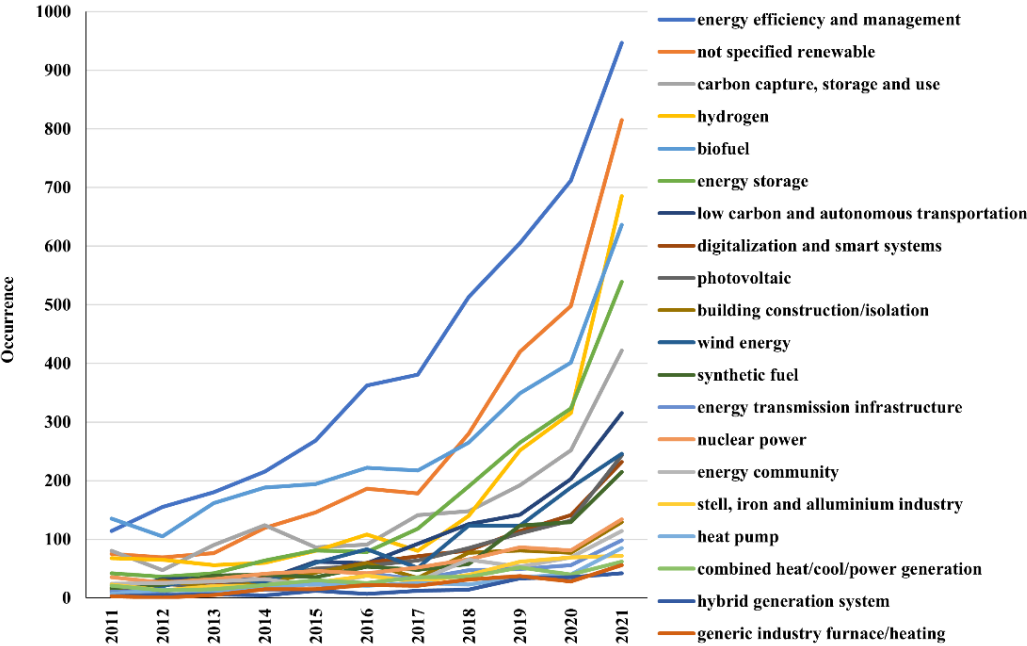


Figure 23 - Occurrence values

In the first step, the domains are ranked based on their relevance and occurrence values. The domain with a higher relevance value is given the first position on the relevance rank, followed by the domain with the second-highest relevance value, and so on. The same procedure is followed for occurrence values.

In the second step, the domains are ranked by calculating the sum of their individual ranks. However, the domain with the lower sum of values is given the first position. It is important to note that if two domains have the same rank, TIM's sort is applied, as this software prioritizes the location of the terms in the documents. Figure 24 evidences the used approach.

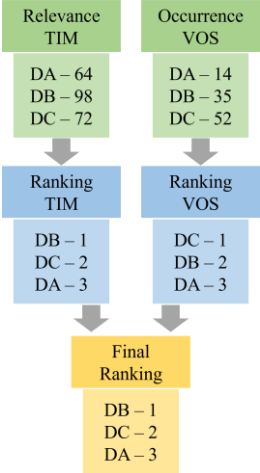


Figure 24 - Approach to rank the domains

Figure 25 shows the global rank obtained using the proposed ranking methodology.

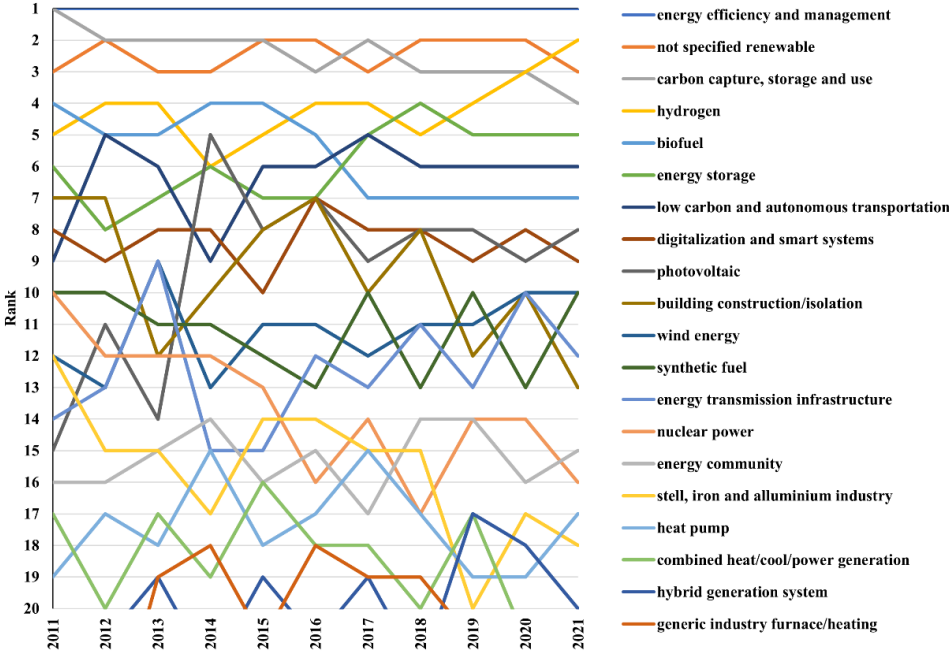


Figure 25 - Rank of technologies domains

The obtained rank allows us to infer that “energy efficiency/management”, “hydrogen technology”, “generic renewable energy”, “carbon capture storage and use”, “energy storage”, and “biofuels” appeared in the last years, as the six better-ranked domains of technologies.

Normalising the relevance/occurrence values by dividing the individual values by their sum makes understanding each technology domain’s relative weight over time possible. Figure 26 and Figure 27 show the normalised values for the 20 previously referred domains.

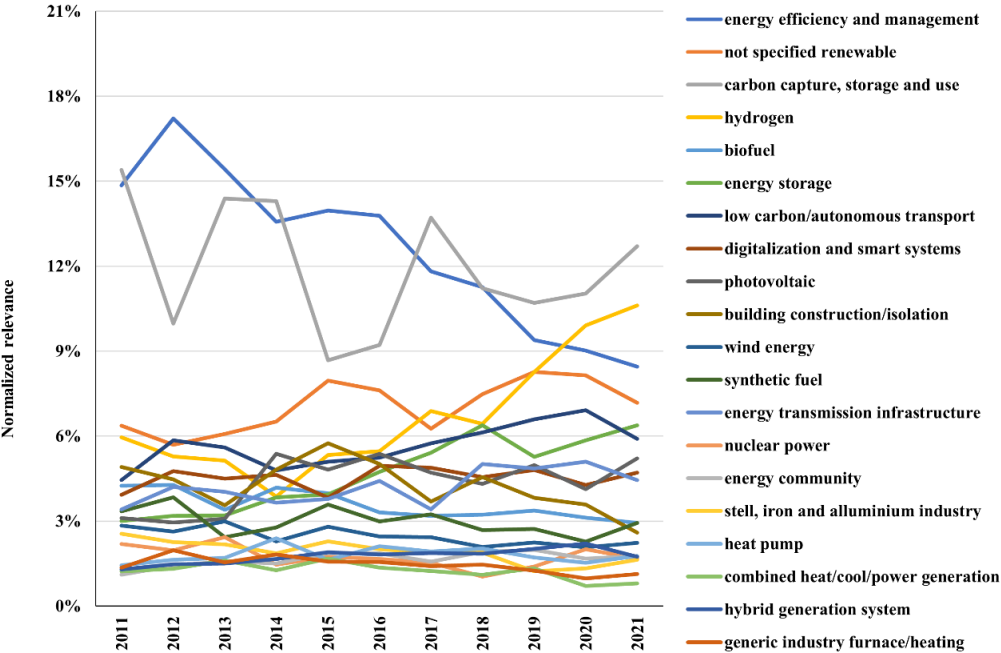


Figure 26 - Normalised relevance

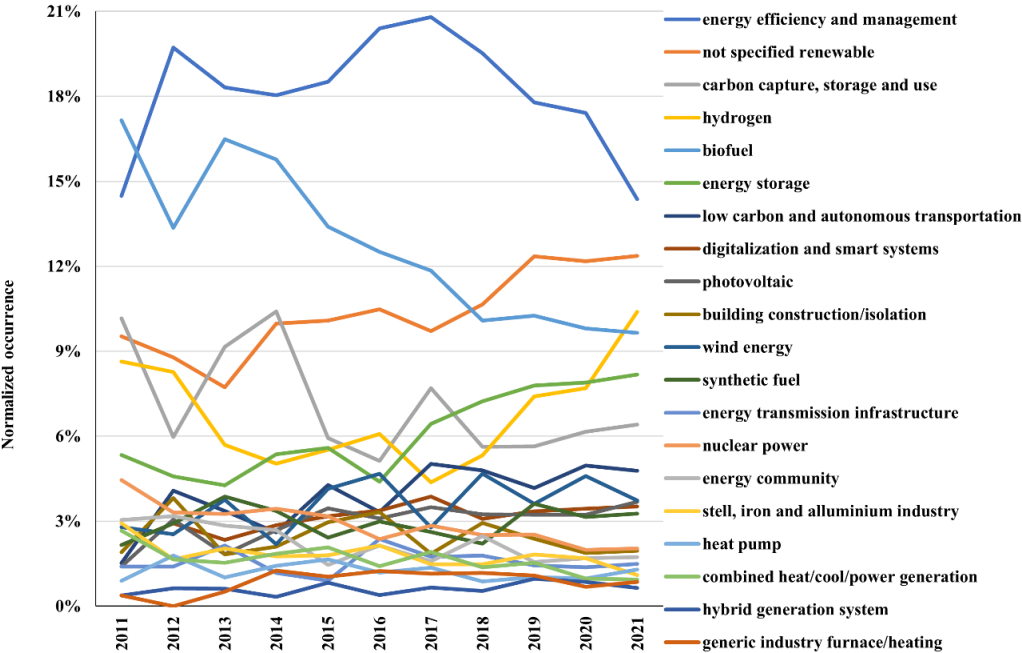


Figure 27 - Normalised occurrence

The data provided by these figures facilitates the identification of the domains that, in recent years, have increased their interest in the scientific community. This has been the case of “hydrogen”, “carbon capture storage and use”, and “energy storage” domains in the last three years. On the other hand, it is also possible to perceive which domains have lost relative interest, such as “energy efficiency and management”, “biofuel”, and “low-carbon transportation”. Note that a lower relative relevance/occurrence value does not necessarily mean reducing the absolute relevance/occurrence values. For example, in the case of “energy efficiency and management”, it is possible to notice an increase in relevance/occurrence values in recent years (Figure 22 and Figure 23) despite the decrease in relative relevance/occurrence values (normalised). In practice, this means that other technology domains have experienced a more accelerated increase in their absolute relevance/occurrence value.

To better understand how the scientific community’s interest in the various domains of technologies has evolved, the nine years between 2013 and 2021 were divided into three-year periods. For each of these periods, the average value of relevance/occurrence for each domain was calculated. The calculated average value allows for mitigating the effects of annual variations that tend to occur in the relevance/occurrence values. Figure 28 and Figure 29 show the variation in the average value of relevance and occurrence, respectively.

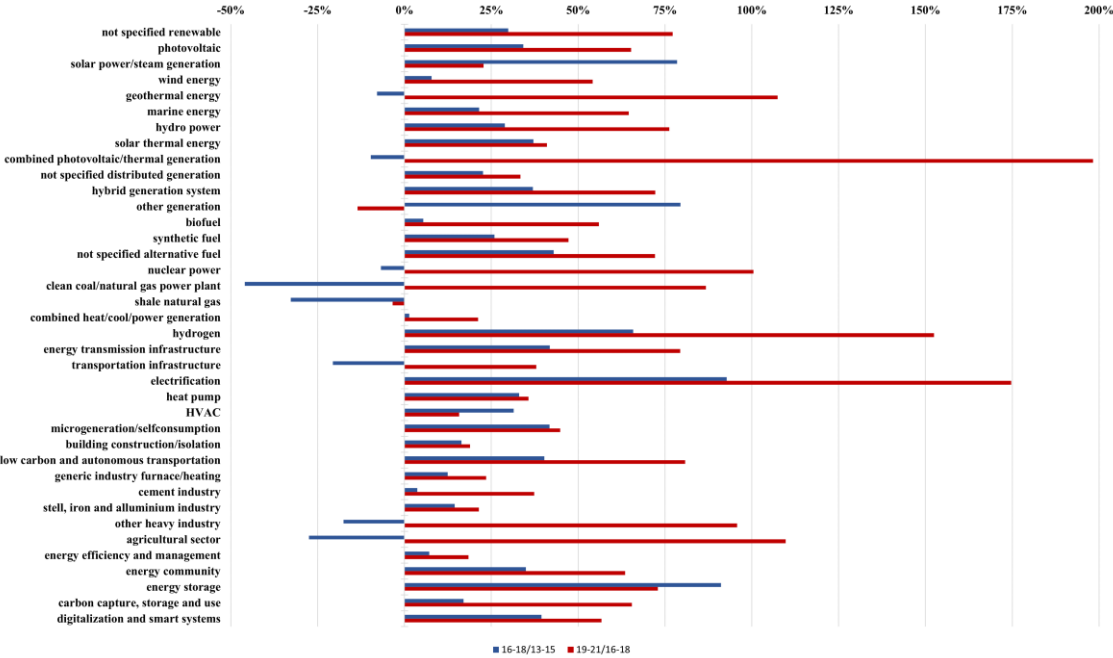


Figure 28 - Variation of the average value of relevance

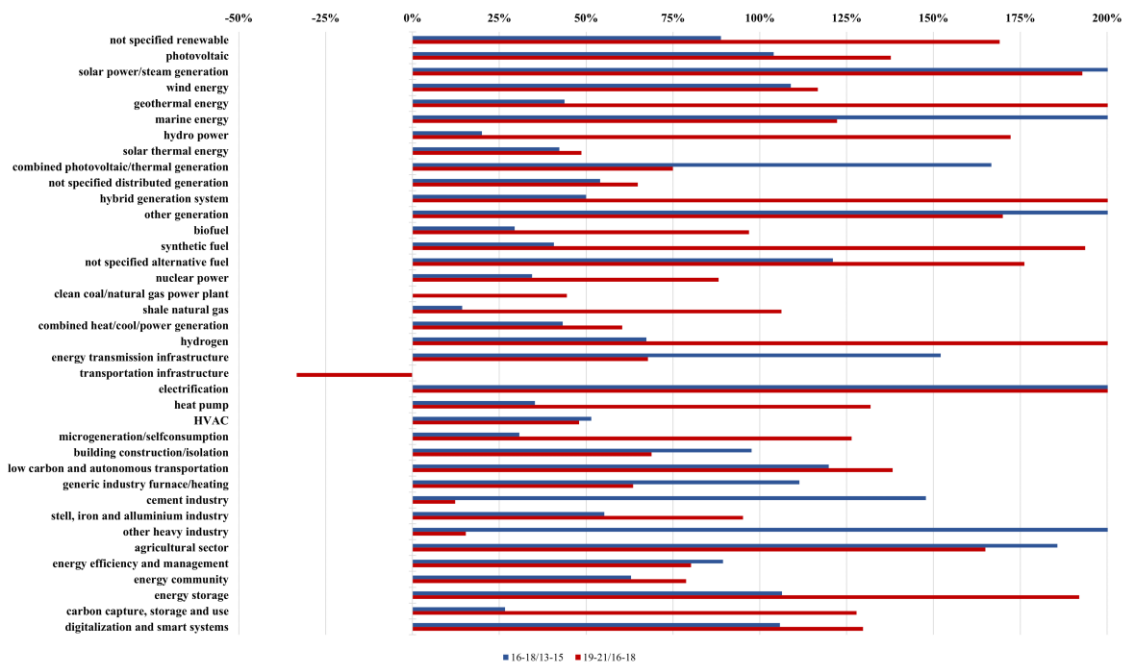


Figure 29 - Variation of the average value of occurrence

By analysing the information, it is possible to verify the existence of technology domains with a significant increase in relevance/occurrence in the 2019-2021 period compared to the 2016-2018 period. In the case of relevance, “combined photovoltaic/thermal generation”, “electrification”, “hydrogen”, “agricultural sector”, “geothermal energy”, and “nuclear power” stand out. Concerning occurrence, “electrification”, “hydrogen”, “hybrid generation systems”, “geothermal energy”, “synthetic fuel”, and “solar power/steam generation” emerge as the six domains with higher increase. Note that “electrification”, “hydrogen”, and “geothermal energy” domains materialise in both the relevance and occurrence indicators. As previously anticipated, “energy efficiency and management”, “biofuel”, and “low carbon transportation” present a significantly lower increase in their relevance and occurrence values in the last three years period.

To comprehensively understand the relevance and the occurrence of the top 20 domains over the entire study period, graphs were generated to showcase their cumulative relevance and occurrence values. Figure 30 and Figure 31 shows the obtained graphs.

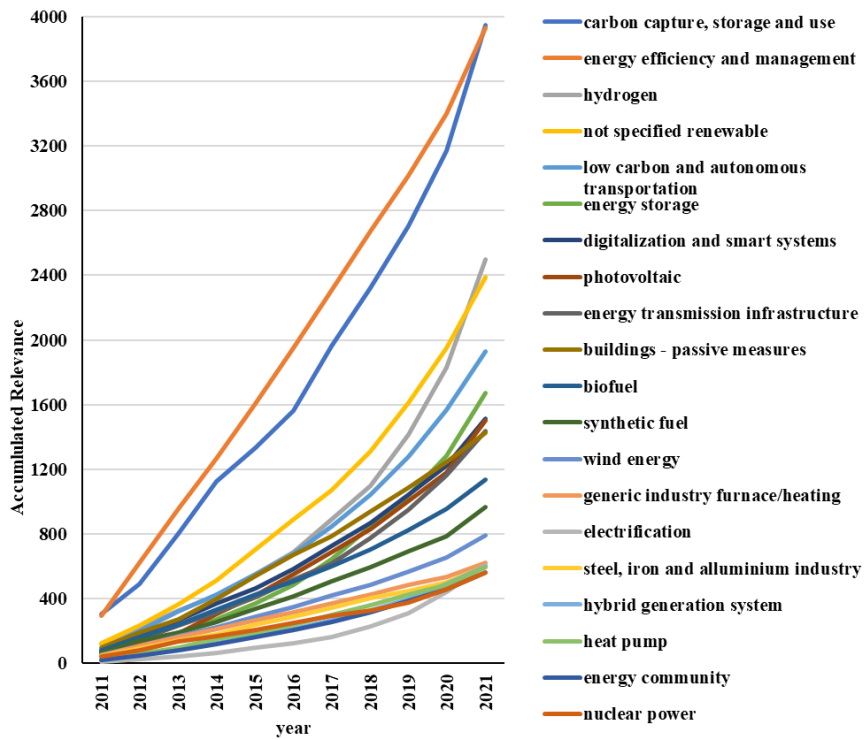


Figure 30 - Accumulated Relevance – Top 20 ranked domains

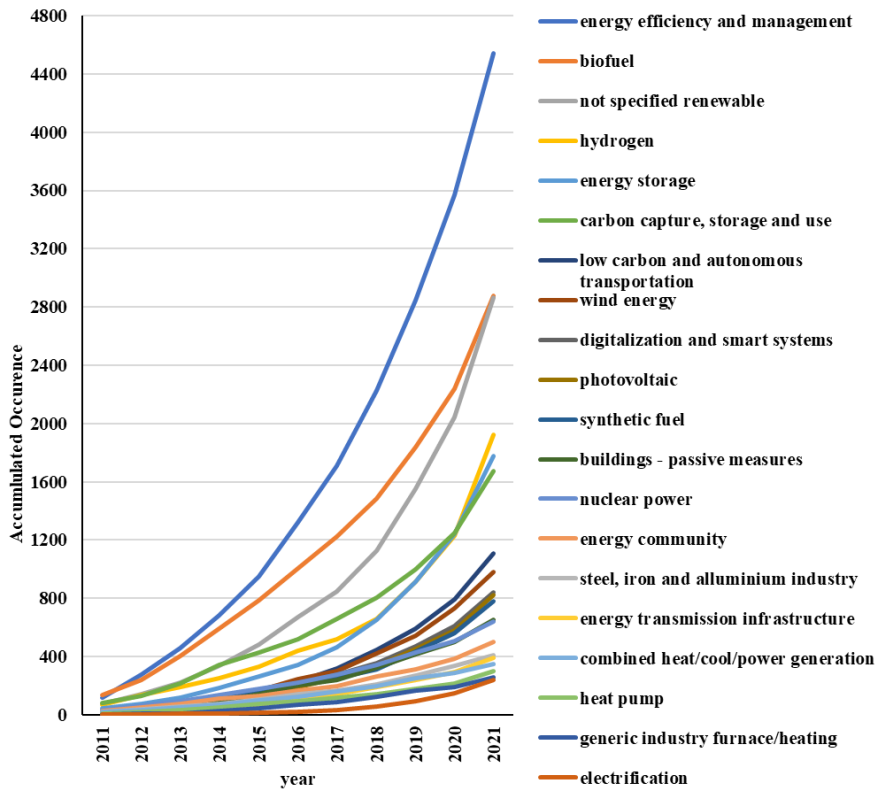


Figure 31 - Accumulated Occurrence – Top 20 ranked domains

It is important to stress that the top 20 ranked domains account for more than 87% of total accumulated relevance and 93% of the total accumulated occurrence. Moreover, eight domains coincide in the top 10 with higher relevance and occurrence: “carbon capture, storage, and use”, “energy efficiency and management”, “hydrogen”, “not specified renewable”, “low-carbon and autonomous transportation”, “energy storage”, “digitalization and smart systems”, and “photovoltaic”. Note that the top ten most relevant domains account for approximately two-thirds of the total relevance. In comparison, the top ten most occurrent domains contribute to three-quarters of the total occurrence.

The accumulated values of relevance and occurrence were normalised to determine how the domains in the top 20 gained or lost attention from the academic community over the years. The normalisation process was carried out annually and involved dividing the total accumulated values of each technology domain by the sum of the accumulated values across all 41 defined domains. Analysing relative relevance and occurrence, shown in Figure 32 and Figure 33, can provide valuable insights.

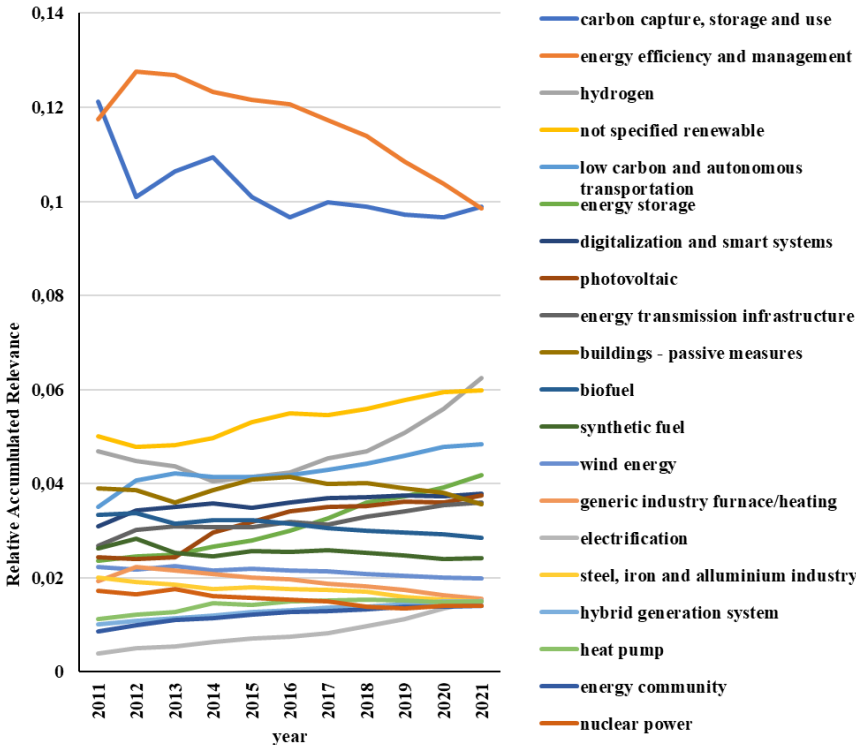


Figure 32 - Relative accumulated relevance

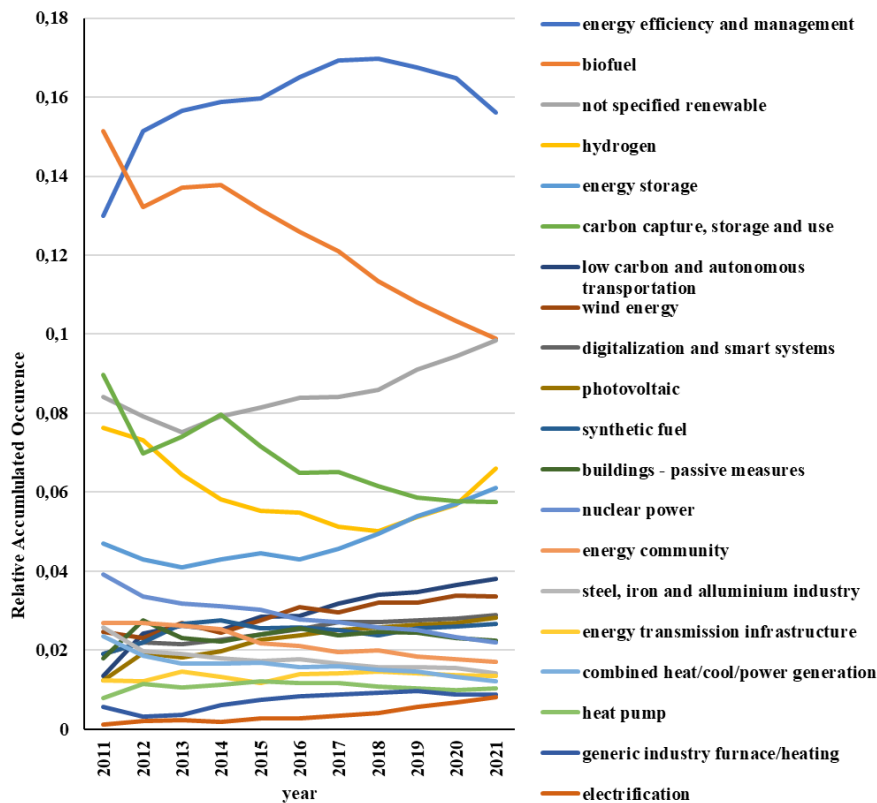


Figure 33 - Relative accumulated occurrence

During the period between 2011 and 2021, the domains of “energy efficiency and management”, “carbon capture, storage and use”, “not specified renewable”, and “hydrogen” demonstrated the utmost relevance. However, the “carbon capture, storage, and use” and the “energy efficiency and management” domains experienced a decline in the value of the accumulated relative relevance. The “biofuel”, “buildings - passive measures”, and “nuclear power” domains have also experienced a decrease in relative accumulated relevance. On the other hand, “hydrogen” (a remarkably rapid increase), “not specified renewable”, “low-carbon and autonomous transportation”, “energy transmission infrastructure”, “energy community”, “energy storage”, and “electrification” domains have gained relative interest.

Concerning the relative value of accumulated occurrence, “energy efficiency and management”, “biofuel”, and “not specified renewable” domains appear as the ones that present higher values. Among the domains that increased their values of relative accumulated relevance, only the “electrification” domain does not also account for an increase in the relative accumulated occurrence. The domains that lost relative interest in relevance have also declined in occurrence.

3. ASSESSMENT OF READINESS, RISKS, AND POTENTIAL OF DECARBONISATION PATHWAYS

To effectively address the pressing issue of decarbonization, it is crucial to assess the readiness, risks, and potential associated with different decarbonization pathways. This assessment allows informed decisions concerning prioritising actions that may lead to a sustainable, low-carbon future.

Readiness refers to the preparation of the decarbonisation pathways to undertake decarbonization efforts. It involves aspects related to the maturity of the innovative technologies.

Risks associated with decarbonization pathways concerning technological limitations must be carefully evaluated to ensure successful implementation. Therefore, the risk analysis done in this work tries to measure the suitability of domains to support decarbonisation in the short term by considering the ratio between ranks of relevance and occurrence and the maturity of the technologies within those domains.

Evaluating the environmental performance of each decarbonisation pathway entails crucial information on their potential. Therefore, the potential of the pathways for reducing emissions is assessed considering the potential for reducing emissions of a set of innovative technologies.

This chapter assesses the paths to decarbonization defined in Work Package 1 of the *Sus2Trans* project regarding readiness, risk and potential. That assessment was based on information on innovative technologies from a database linked to the International Energy Agency's (IEA) Energy Technology Perspectives 2020 [48]. This comprehensive database encompasses 368 distinct technology designs and components spanning the entire energy system, all contributing to the objective of achieving net-zero emissions. Each technology entry in the database includes details on its maturity level, development and deployment plans, cost and performance improvement targets, and key players in the field. Moreover, a suitable maturity scale was adopted for the assessment process.

3.1. Metric for measuring technology readiness

Some different scales to measure technologies' current state of maturity may be found in the literature. The most widely used method is the Technological Readiness Level (TRL), a consistent approach to compare the maturity of different technologies.

TRL scales with different levels can be found in the literature. For instance, a nine levels scale is presented in [49]:

- TRL 1 - Basic principles observed.
- TRL 2 - Formulated technology concept.
- TRL 3 - Experimental proof of concept.
- TRL 4 - Technology validated in the laboratory.
- TRL 5 - Technology validated in a relevant environment.
- TRL 6 - Technology demonstrated in a relevant environment.
- TRL 7 - Demonstration of the system prototype in an operating environment.
- TRL 8 - Complete and approved system.
- TRL 9 - The real system is proven in the operating environment.

The technologies for which the basic research has been carried out, the fundamental concept has been investigated, and the proof of the concept has been developed are categorized at levels one to three. Levels four and five correspond to validated technologies, which implies the development of prototypes. The technologies already demonstrated in relevant and operational environments are incorporated in levels six and seven of TRL. The highest TRL levels, specifically levels eight and nine, involve effective production of the technologies, proving their correct functioning.

The International Energy Agency (IEA) uses a different scale of TRL to characterize the maturity of technologies [50]. This scale is divided into 11 levels, as illustrated in Figure 34.



Figure 34 - TRL scale adopted by IEA (Source: [50])

Regardless of the scale, emerging technologies are categorized at the lowest TRL, while commercially available technologies are classified at the highest TRL. However, it is essential to note that a specific technology domain encompasses various solutions (or particular technologies). This situation implies that assigning a single TRL value to a technology domain may not accurately reflect its status. Instead, a range of TRL values may represent the maturity of technology domains [49]. Thus, a TRL ranging from 2 to 9 to a specific technology domain indicates the presence of both already commercialized technologies and those that still require significant development. Consequently, technology domains with an extended TRL range are subjected to greater uncertainty, making them riskier for investment. Conversely, narrower TRL ranges associated with higher average TRL values suggest that the technology domains are more mature and less risky [51].

The TRL scale of IEA is used in this work. Moreover, a qualitative scale that groups the TRL values of the above quantitative scale was defined to facilitate the perception of the state of maturity of the various technologies. This qualitative scale includes five stages of maturity, namely:

- **Concept stage (TRL 1 to 3)** – conceptual idealisation of the technology, usually based on theoretical studies;
- **Prototype stage (TRL 4 to 6)** – implementation of practical prototypes that allow proving the idealised concept;
- **Commercialisation ready stage (TRL 7 and 8)** – the technology has been proven and is seen as a final product ready to start being commercialised;
- **Dissemination stage (TRL 9 and 10)** – the technology is commercially available and competitive. However, additional efforts are required for its dissemination;
- **Proven technology stage (TRL 11)** – the technology is established, and its use is expected to grow.

Figure 35 shows the correspondence between the above quantitative and qualitative scales.

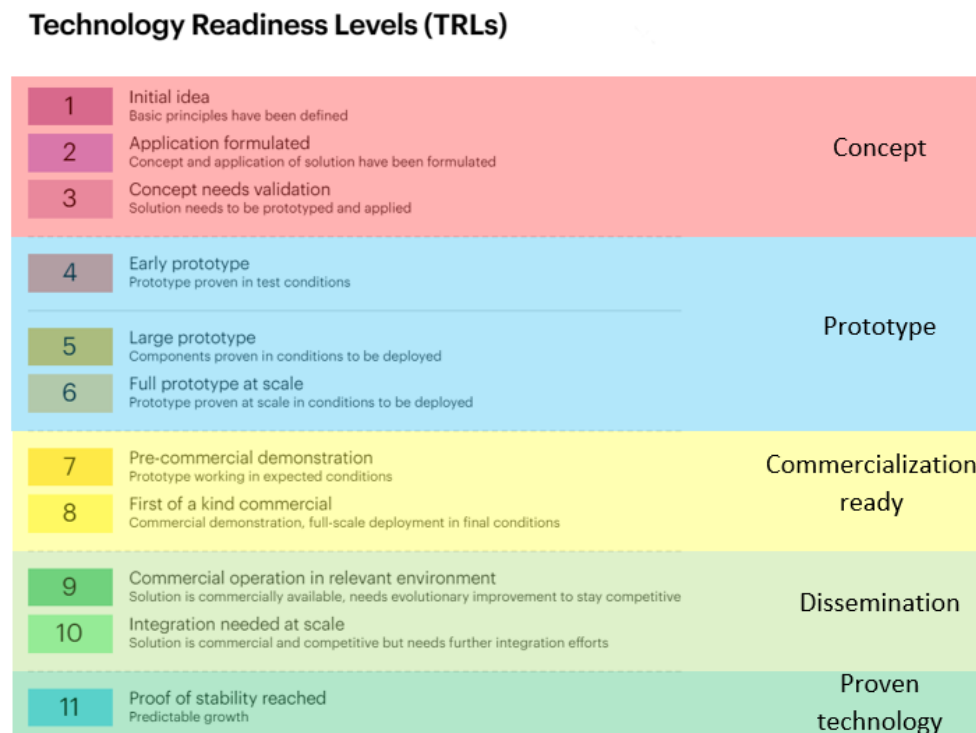


Figure 35 - Correspondence between quantitative and qualitative TRL scales

3.2. Innovative technologies for decarbonisation

The availability of innovative technologies greatly influences the implementation of a specific pathway for decarbonisation. Moreover, the state of maturity of those technologies plays a crucial role in defining decarbonisation policies, especially when considering short-term goals.

This work considered innovative technologies from a database linked to the IEA's Energy Technology Perspectives 2020 [48]. This comprehensive database encompasses 368 distinct technology designs and components spanning the entire energy system, all contributing to the objective of achieving net-zero emissions. Each technology entry in the database includes details on its maturity level, development and deployment plans, cost and performance improvement targets, and key players in the field. Figure 36 provides a comprehensive overview of the mentioned technologies. The same figure, with better readability, can also be found in ANNEX A. The IEA also makes available an Excel file titled Energy Technology Perspectives 2020 - The ETP technology tree for long-term clean energy transitions, where more complete information is given. Figure 37 shows an extract of this file.

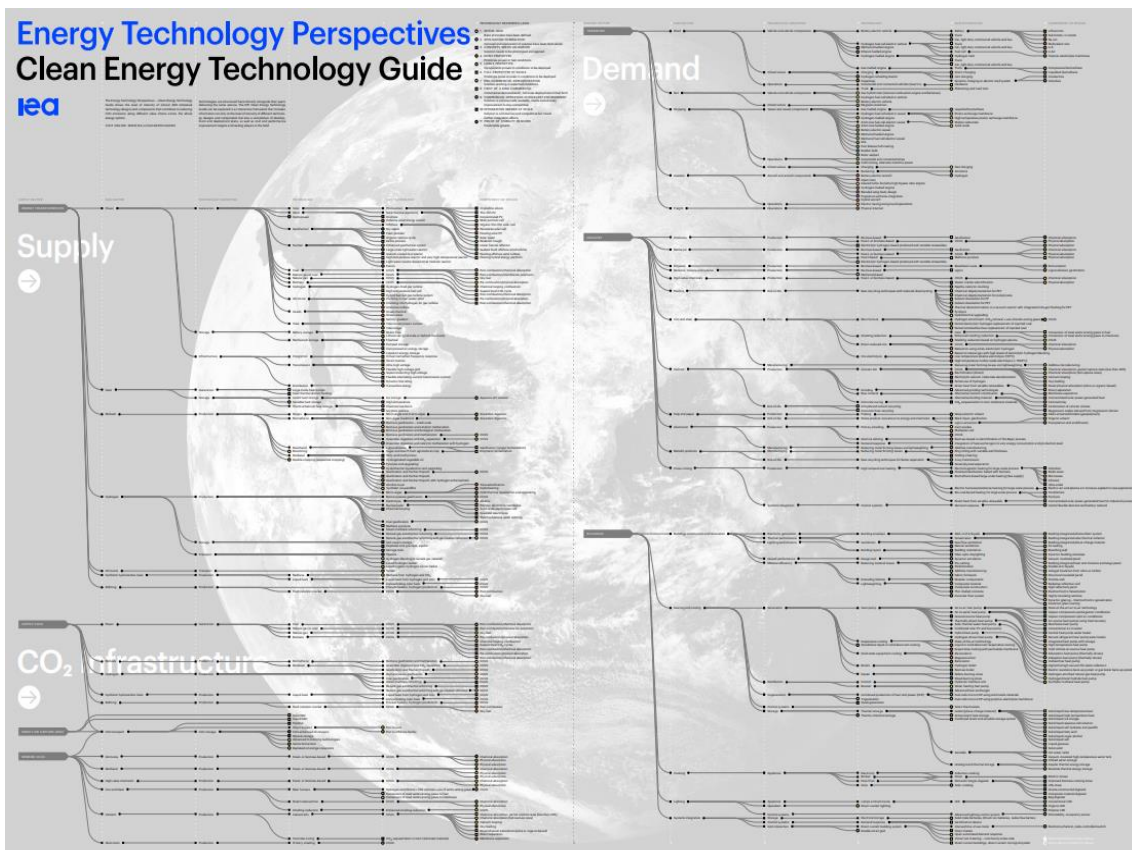


Figure 36 - IEA innovative decarbonisation technologies (Source: [52])

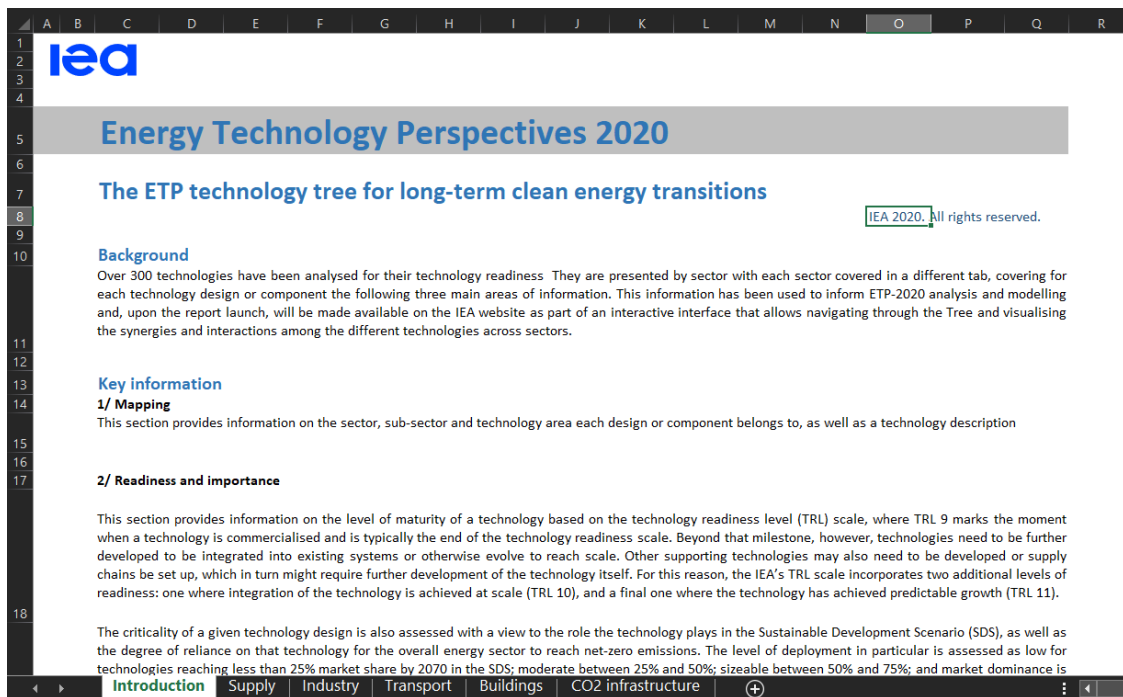


Figure 37 - Extract of the IEA Excel file with information about innovative decarbonisation technologies

The 368 technologies/components are divided into three main groups: supply-side technologies, demand-side technologies (Industry, Transport and Buildings sheets) and CO₂ infrastructure. Figure 38 shows that 65% of those technologies/components (239) belong to the demand-side group. As expected, the CO₂ infrastructures present fewer technologies (10). The supply-side technologies account for 32% of the total technologies (119).

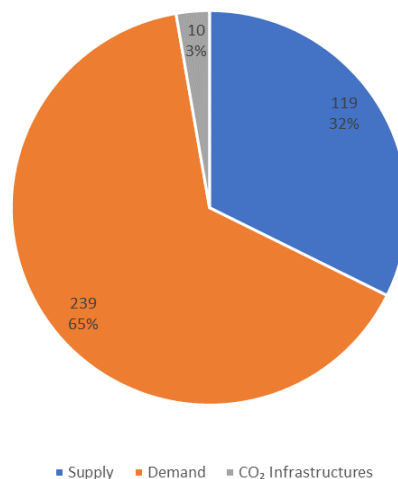


Figure 38 - Innovative technologies according to the side they are integrated

The Excel file contains relevant information about the innovative technologies, including the respective TRL, as seen in the extracts presented in the following figures (Figure

39 to Figure 43). Note that not all available data in the Excel file is shown on those figures. Moreover, the figures show the subdivision of the demand-side technologies into three groups: industry, transport, and buildings sectors.

Mapping							
Demand/Supply	Sector	Sub-Sector or Technology	Technology, grouping or sub-sector	Technology/Sub-technology/component (if applicable)	Technology/Sub-technology/component (if applicable)	Technology Description	TRL
Supply	Power	Power generation	Solar	Photovoltaic	Crystalline silicon	Today, the vast majority of PV modules are based on wafer-based crystalline silicon (c-Si). The manufacturing of c-Si modules typically involves growing ingots of silicon, slicing the ingots into wafers to make solar cells, electrically interconnecting the cells, and encapsulating the strings of cells to form a module. Modules currently use silicon in one of two main forms: single- (sc-Si) or multi- (mc-Si) crystalline modules. Current commercial single-crystalline modules have a higher conversion efficiency of around 14 to 20%. Their efficiency is expected to increase up to 25% in the longer term. Multi-crystalline silicon modules have a more disordered atomic structure leading to lower efficiencies, but they are less expensive. Their efficiency is expected to increase up to 21% in the long term.	9-10
Supply	Power	Power generation	Solar	Photovoltaic	Thin-film PV	A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers, or thin film (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. Although emerging thin-film solar technologies may be more expensive to make than conventional silicon, their lighter weight and greater resilience can fill niches in the energy sector	8
Supply	Power	Power generation	Solar	Photovoltaic	Concentrated PV	Concentrated PV (CPV) technologies use an optical concentrator system which focuses solar radiation onto a small high-efficiency cell. CPV modules can achieve efficiencies of above 40%	9-10
						Multi-junction cell design involves superposing several cells in a stack. In the case	

Figure 39 - Extract of technologies from the supply side group

Mapping							
Demand/Supply	Sector	Sub-Sector or Technology	Technology, grouping or sub-sector	Technology/Sub-technology/component (if applicable)	Technology/Sub-technology/component (if applicable)	Technology Description	TRL
Demand	Industry	Ammonia production		Carbon Capture	Physical separation	Physical separation is based on adsorption, in which molecules are captured on the surface of selective materials that are called adsorbent. It can be grouped in pressure swing adsorption (PSA), performed at high pressure, and vacuum swing adsorption (VSA), which operate at ambient pressure. An hybrid configuration also exists, the Vacuum Pressure Swing Adsorption (VPSA).	5
Demand	Industry	Methanol production	Electrolytic hydrogen and CO2			Methanol production requires producing a synthetic gas composed of CO, CO2 and hydrogen, which react afterwards into methanol. This process relies on hydrogen produced from water electrolysis and waste CO2 from industrial processes.	7
Demand	Industry	Methanol production	Biomass			Biomass can replace oil, natural gas and coal as a feedstock for methanol production. The biomass feedstock is converted into syngas, which is then conditioned for methanol synthesis.	8
Demand	Industry	Methanol production		Carbon Capture	Chemical Absorption	Chemical absorption of carbon dioxide (CO ₂) is a common process operation based on the reaction between CO ₂ and a chemical solvent (e.g. amine-based). The CO ₂ is released at high temperature and the solvent regenerated for further operation.	7

Figure 40 - Extract of technologies from the demand side group – Industry sector

Mapping							
Demand/Supply	Sector	Sub-Sector or Technology	Technology, grouping or sub-sector	Technology/Sub-technology/component (if applicable)	Technology/Sub-technology/component (if applicable)	Technology Description	TRL
	Demand	Transport	Road	Battery Electric Vehicle (BEV)	Solid state + Li-metal	This battery technology offers scope for major performance improvements in energy density and fire safety, in comparison to lithium-ion, thanks to an inorganic solid electrolyte (Lithium-ion batteries use organic liquid electrolytes). The solid electrolyte would also allow the use of lithium metal as an anode material, with further major energy density improvement prospects (however the use of Li-metal brings additional development hurdles as well as increased hazard if ignited due to a high lithium content).	5
	Demand	Transport	Road	Battery Electric Vehicle (BEV)	Na-ion	The working principle and components for most proposed Na-ion batteries are rather similar to Li-ion ones, only the conductor material differs (sodium instead of lithium).	4
	Demand	Transport	Road	Battery Electric Vehicle (BEV)	Multivalent ions	The proposed concept for this technology is to use a material that is able to transport more than one electron for each atom. Commonly studied materials for this concept are Magnesium, Calcium and Aluminium. They offer the potential for very high energy density and a move away from Lithium and other scarce materials. The technology is still at early stages of development.	2
	Demand	Transport	Road	Battery Electric Vehicle (BEV)	Li-S	This battery uses lithium as an anode and electron-transfer material, while sulphur makes up the cathode. This concept offers the prospect of very high energy density and does not require expensive cathode materials. This chemistry already has a long history of development but efforts are currently ramping up. Prototype cells have already been developed with energy densities above 400 Wh/kg and the main challenge (beside improving the availability of the raw materials) is to improve the cycle life of the battery.	3-4

Figure 41 - Extract of technologies from the demand side group – Transport sector

Mapping								
Demand/Supply	Sector	Sub-Sector or Technology	Technology, grouping or sub-sector	Technology/Sub-technology/component (if applicable)	Technology/Sub-technology/component (if applicable)	Technology Description	TRL	
	Demand	Buildings	Building envelope	Wall, roof & façade	Structural Insulated Panels	Heat protection: structural insulated panels oriented-strand board or side of an insulating core	9	
	Demand	Buildings	Building envelope	Wall, roof & façade	Trombe wall	Heat gain from the sun: storage and solar heating walls in components with high thermal mass which leads to indirect heat gains, they encompass a range of designs including classic, composite, water, zitag, solar trans-wall, fluidized and photovoltaic	7	
	Demand	Buildings	Building envelope	Wall, roof & façade	Radiative Reflective Roofs	Heat rejection: sky-facing surface with optical and thermal properties for dissipating terrestrial heat to outer space	7	
	Demand	Buildings	Building envelope	Wall, roof & façade	High reflectivity paint	Building design: paints that provide the same visible colour range as standard products but exploit the infra-red spectrum to reflect a greater part of the solar irradiation spectrum.	10	
	Demand	Buildings	Building envelope	Building design	Building orientation	For thermal needs	Heat gain from the sun and ventilation: optimal building orientation to allow solar radiation penetration in the winter and ventilation in the summer, by facing the summer wind stream	11
	Demand	Buildings	Building envelope	Building design	Building orientation	For lighting	Building design: attention to building design to maximize daylight in the building through for example window placement, light shelves, shorter partitions	11
	Demand	Buildings	Building envelope	Building design	Fiber-optic daylighting	Building design: fiber optics combined with solar light collectors to transmit daylight in zones usually hard to daylight, also called "remote source lighting".	6	
	Demand	Buildings	Building envelope	Fenestration	Electrochromic Fenestration	Heat protection: window able to change transmittance, solar heat gain coefficient and visible transmittance, energized by electrical current	7	

Figure 42 - Extract of technologies from the demand side group – Buildings sector

Mapping							
Demand/Supply	Sector	Sub-Sector or Technology	Technology, grouping or sub-sector	Technology/Sub-technology/component (if applicable)	Technology/Sub-technology/component (if applicable)	Technology Description	TRL
Direct Air Capture							
			Direct Air Capture (DAC)	Solid DAC (S-DAC)		Solid Direct Air Capture (S-DAC) is a technology aiming at capturing carbon dioxide (CO ₂) from the atmosphere and either use it as a feedstock or store it underground. This technology relies on amine materials bonded to a porous solid support. CO ₂ is initially chemically bounded to the solid filter, and then released once the filter is saturated by warming it up to 80-100°C.	6-8
			Direct Air Capture (DAC)	Liquid DAC (L-DAC)		Liquid Direct Air Capture (L-DAC) is a technology aiming at capturing carbon dioxide (CO ₂) from the atmosphere and either use it as a feedstock or store it underground. This technology relies on aqueous solutions containing hydroxide solvents with a strong affinity for CO ₂ (e.g. sodium hydroxide, calcium hydroxide and potassium hydroxide). These aqueous solutions allow the continuous operation of the DAC system, with long contactor lifetimes despite atmospheric contaminants. On the other hand, they rely on regeneration systems cooling at very high operating temperatures (around 300°C).	6-8
CO₂ transport							
			CO ₂ transport	Pipeline		CO ₂ transport links CO ₂ from capture sites with geological storage locations or sites where CO ₂ is used. After capture, the CO ₂ is compressed into liquid or supercritical phase to make it ready for transport. Pipelines are typically more cost-effective for large quantities.	9
			CO ₂ transport	Ship transport	Port-to-port	CO ₂ transport links CO ₂ from capture sites with geological storage locations or sites where CO ₂ is used. After capture, the CO ₂ is compressed into liquid or supercritical phase to make it ready for transport. Shipping offers greater flexibility but takes place in discrete cycles and therefore requires appropriate	6-7

Figure 43 - Extract of technologies from the CO₂ infrastructure group

The map in Figure 36 illustrates the subdivision of technologies in the CO₂ Infrastructures group into three subgroups: Capture, Storage, and Transportation of CO₂. Moreover, those technologies focus on the atmospheric CO₂, making them negative emissions technologies. Consequently, there is a distinction between these technologies and carbon capture and storage (CCS) facilities utilized in other processes (e.g., electricity generation in a natural gas-fired power plant) to capture the emissions produced by these processes. For the scope of this study, we classify those last CCS technologies as mitigation technologies.

The supply-side technologies are also grouped into three sectors: Power, Heat, and Other fuel transformation. Figure 44 shows the relative weight of those groups.

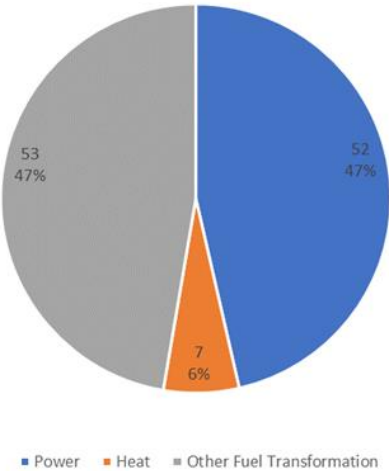


Figure 44 - Sectors of technologies on the supply side

Table 4 summarises the sectors, subsectors and types of technologies included in the supply-side group. Power generation is the most significant subsector of the Power sector, representing 78% of the technologies/components. Power storage and electrical grids contain 10.2% and 11.8% of the technologies, respectively.

Table 4 - Summary of the supply-side technologies

Supply side						
Sector	Sub-sector	Technology	Nr	Total		
Power	Power generation	Solar	10	46	Renewable	
		Wind	4			
		Hydropower	1			
		Geothermal	5			
		Biomass	2			
		Tidal	2			
		Ocean	3			
		Nuclear	6			Nuclear
		Hydrogen	3			Synthetic
		Ammonia	3			Synthetic
		Coal	5			Fossil
	Natural Gas	2				
	Power storage	Battery storage	3	6		
		Mechanical storage	3			
Electrical Grids	Integration	1	7			
	Transmission	5				
Heat	Heat generation	Distribution	1	2		
		Large scale heat pump	1			
	Thermal storage	Solar-thermal district heating	1			
		Sensible heat storage	1			
		Latent heat storage	2			
		Thermochemical heat storage	2			
Other fuel Transformation	Biofuels production	Biodiesel	12	29		
		Biogas	3			
		Biomethane	7			
		Bioethanol	5			
		Biorefining	1			
		Double-cropping	1			
	Hydrogen production	Biomass	1	11		
		Electrolysis	4			
		Fossil-derived	6			
	Hydrogen storage	Salt cavern storage	1	3		
		Depleted oil & gas fields, aquifers	1			
		Storage tanks	1			
	Hydrogen transport	H2 pipeline	1	3		
		Liquid H2 tanker	1			
		LOHC tanker	1			
	Ammonia transport	Tanker	1	1		
	Synthetic Hydrocarbon Fuels production	Methane from H2 + CO2	1	3		
Liquid fuels from H2 + CO2		1				
Concentrating solar fuels		1				
Refineries	Process heaters, hydrogen production	1	3			
	Fluid catalytic cracker	2				

Concerning the heat sector, just seven technologies are considered (5.9% of all supply-side technologies/components). Furthermore, 71.4% of those technologies are related to thermal storage technologies.

Biofuels represent more than half (54.7%) of the fuel transformation sector's technologies/components, and hydrogen-related technologies correspond to 32.1%.

From a more global view, power generation (39%), biofuels (24%) and hydrogen-related technologies (13%) represent more than three-quarters of the supply-side technologies considered by the IEA.

Figure 45 shows the weight of each sector considered for the demand-side group, where it is possible to conclude that the building sector contains almost half (45%) of the technologies/components of the demand-side group.

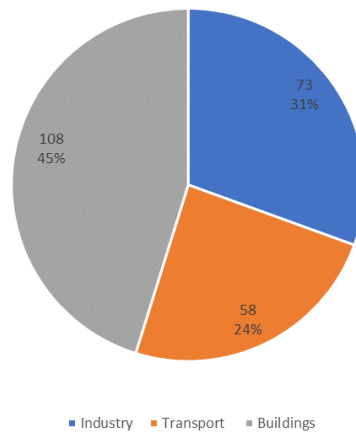


Figure 45 - Sectors of technologies on the demand side

Table 5, Table 6 and Table 7 summarise the sectors, subsectors and types of technologies included in the demand-side group.

Material efficiency (21.1%), Cement (18.3%) and Iron and Steel (16.9%) are the more relevant segments of the Industry sector, totalising 56.3% of the total number of technologies included in that sector.

In the transport sector, the big bet is on the road segment, which accounts for almost half (46.6%) of the technologies assessed. Electrification, synthetic fuel engines, and designs are the leading technologies for the shipping and aviation segments.

The heating and cooling segment plays a crucial role in the overall building sector, encompassing over one-third (34%) of the technologies analyzed by the IEA. Furthermore, an impressive majority (72%) of the technologies considered in this sector can be achieved by combining the heating and cooling segment with the building envelope (19%) and system integration (19%) segments.

Table 5 - Summary of demand-side technologies in the Industry sector

Demand side				
Sector	Sub-sector	Technology	Nr	Total
Industry	Ammonia production	Electrolytic hydrogen and CO2	1	3
		Biomass	1	
		Carbon capture	1	
	Methanol Production	Electrolytic hydrogen and CO2	1	3
		Biomass	1	
		Carbon capture	1	
	Ethylene production	Bioethanol route	2	2
	BTX Aromatics production	From Methanol	1	1
	High Value Chemicals	Carbon capture	1	2
		Steam Cracker Electrification	1	
	Iron and Steel	Blast Furnace	2	12
		Smelt reduction	2	
		Direct reduced Iron	4	
		Ore electrolysis	2	
		Carbon capture and use	2	
	Cement	Cement kiln	8	13
		Curing processes	1	
		Grinding processes	1	
		Alternative cement constituents	1	
		Alternative binding material	2	
	Pulp & Paper	Waste product conversion to bioenergy	1	4
		Pulping	1	
		Waste product conversion to chemicals and bioenergy	2	
	Aluminium	Primary smelting	2	5
		Alumina refining	1	
		Integration	1	
		Carbon capture and storage	1	
	Material Efficiency	Reducing metal forming losses	4	15
		New recycling techniques for better separation and reduced contamination	2	
		New recycling techniques with reduced downcycling	7	
		Unhydrated cement recycling	1	
		Concrete fines recycling	1	
	Cross-cutting	High temperature heating	7	11
Low to medium temperature heating		4		

Table 6 - Summary of demand-side technologies in the Transport sector

Demand side						
Sector	Sub-sector	Technology	Nr	Total		
Transport	Road	Battery Electric Vehicle (BEV)	8	27		
		Gas Powered Truck	2			
		Hydrogen Fuel Cell Vehicle (FCEV)	4			
		Hydrogen-fuelled vehicle	1			
		Automated and connected vehicles (level 4+)	1			
		Methanol-fuelled vehicle	1			
		Ethanol fuelled truck	1			
		Truck	1			
		Infrastructure	7			
		Physical internet (Freight)	1			
		Rail	Gas Hybrid Train (ICE+Batteries)		1	3
			Hydrogen Fuel Cell Train		1	
			Battery-Operated Train		1	
	Shipping	Battery Electric Ship	1	19		
		Methanol ICE	1			
		Methanol Fuel Cell	1			
		Liquefied Biogas ICE	1			
		Hydrogen Fuel Cell	4			
		Ammonia ICE	1			
		Ammonia Fuel cell	1			
		Kites	1			
		Foul Release Hull Coating	1			
		Rudder Bulb	1			
		Rotor Sail	1			
		Automated and connected ships	1			
		Cold Ironing, Alternate Maritime Power	1			
	Infrastructure	3				
	Aviation	Battery Electric Aircraft	1	9		
		Open Rotor	1			
		Geared Turbo Fan / Ultra-High Bypass Ratio (UHBR) engine	1			
		Hydrogen-Fuelled Aircraft	1			
		Blended Wing Body Design	1			
		Propulsion-Airframe Integration	1			
Hybrid Electric		1				
Battery Electric		1				
electric taxiing	1					

Table 7 - Summary of demand-side technologies in the Buildings sector

Demand side				
Sector	Sub-sector	Technology	Nr	Total
Buildings	Building envelope	Wall, roof & façade	14	21
		Building design	3	
		Fenestration	4	
	Ventilation	Air displacement	1	2
		Building design	1	
	Heating and Cooling	Generation	32	37
		Distribution	1	
		District energy systems	2	
		Cogeneration	2	
	System integration	Generation	1	20
		Cogeneration	2	
		Thermal storage	15	
		Thermo-chemical storage	1	
		Electrical storage	1	
	Cooking	Cooking	8	8
	Lighting	Lamps and luminaries	3	4
		System	1	
	Digitalization	Control systems	3	7
		Grid interaction	4	
Material efficiency	Construction	9	9	

3.3. Maturity of the technologies

3.3.1. Global analysis

As previously referred, the IEA groups of innovative technologies for decarbonisation are categorized into three groups: supply-side, demand-side, and CO₂ Infrastructures side. Figure 46 shows a box plot graph that compares the maturity of the technologies encompassed by each group according to the TRL values present in the IEA information. Note that the figure allows for comparison using the qualitative and quantitative scales referred to in section 3.1.

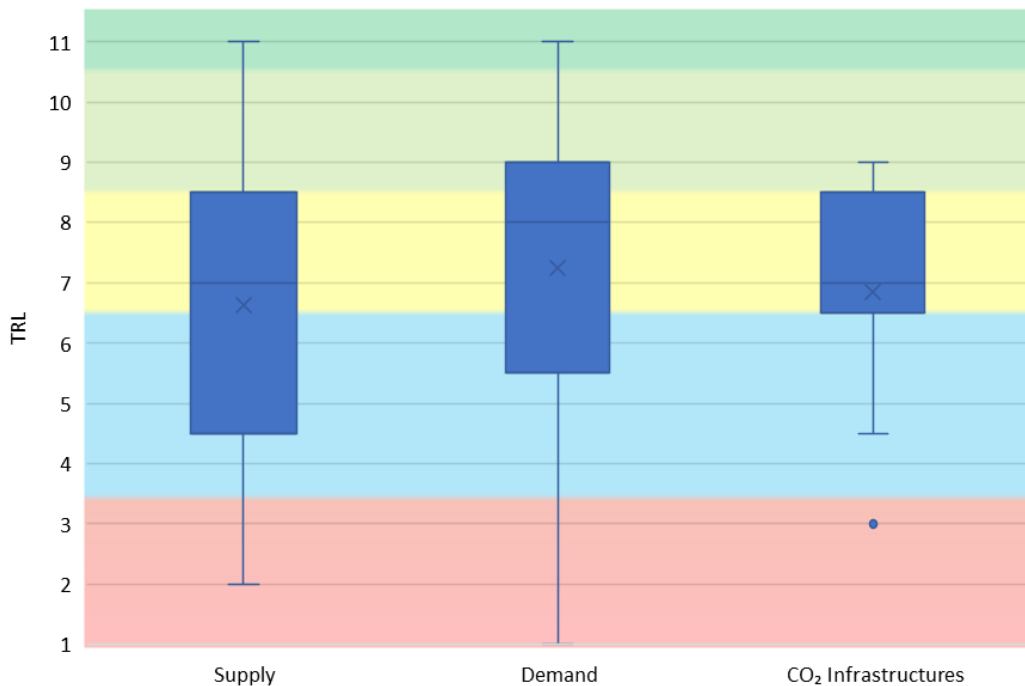


Figure 46 - Maturity of technologies according to the side of the system they belong

Figure 46 allows us to realise that demand-side technologies present higher median (8) and average (>7) TRL values. Moreover, more than 25% of those technologies are already in the dissemination phase or are already proven. However, 25% of those technologies are in the concept or prototype stages (there are two technologies with TRL equal to 1, corresponding to the *carbon capture and storage* at the aluminium smelter industry and *Li-air batteries* for electric vehicles in the transport sector). On the other hand, 3% of the demand-side technologies/components (7) present a TRL of 11. All those technologies belong to the buildings subgroup, including *air-to-air heat pumps*, *wood-based biomass heaters*, *thermal storage in hot water tanks*, *induction* and *electric stoves*, and the *building orientation* considering the thermal and lighting needs.

The supply-side technologies present a lower level of maturity. Indeed, almost 50% of those technologies are in the prototype or concept stages. Nevertheless, 25% of the technologies are already in the dissemination phase or have already been proven. Even so, 4% of those technologies (5) have a TRL of 11: electricity generation through *Hydroelectric* and *Geothermal plants (dry steam and flash process)*, *power storage via pumped systems* and *hydrogen transport via a pipeline*. The lowest TRL for a supply-side technology is 2, corresponding to *nuclear fusion*.

Concerning CO₂ infrastructures, only ten technologies appear in the IEA information. Therefore, the information revealed by the corresponding boxplot may be compromised (due to the small sample size). Even so, it's possible to understand that this group presents a lower level of maturity than demand-side and supply-side technologies. There are no proven technologies. Moreover, just 25% of the technologies are at the beginning of the dissemination process, three of them with TRL of 9: *pipeline for transportation*, *storage in saline formations*, and *storage of CO₂-EOR (enhanced oil recovery)*). Notwithstanding, 50% of the technologies (5) are in a commercialisation-ready stage. The outlier with a TRL of 3 corresponds to *CO₂ storage via mineral storage*.

The classifications established by the IEA, which consists of supply-side technologies, demand-side technologies, and CO₂ infrastructure, lack a specific category for infrastructures that are not directly linked to negative emissions technologies. Therefore, the technologies/components related to transmission, distribution, and energy control infrastructure were included in the supply-side and demand-side groups (such as *High Voltage Direct Current (HVDC) transmission systems*, *Smart Grids*, *dynamic line rating*, etc.).

In this study, a group of infrastructure-related technologies was developed. This group encompasses various technologies and components previously categorized under the supply-side and demand-side groups, as Figure 47 suggests. Note that the technologies associated with the CO₂ infrastructures group were not included in this new grouping.

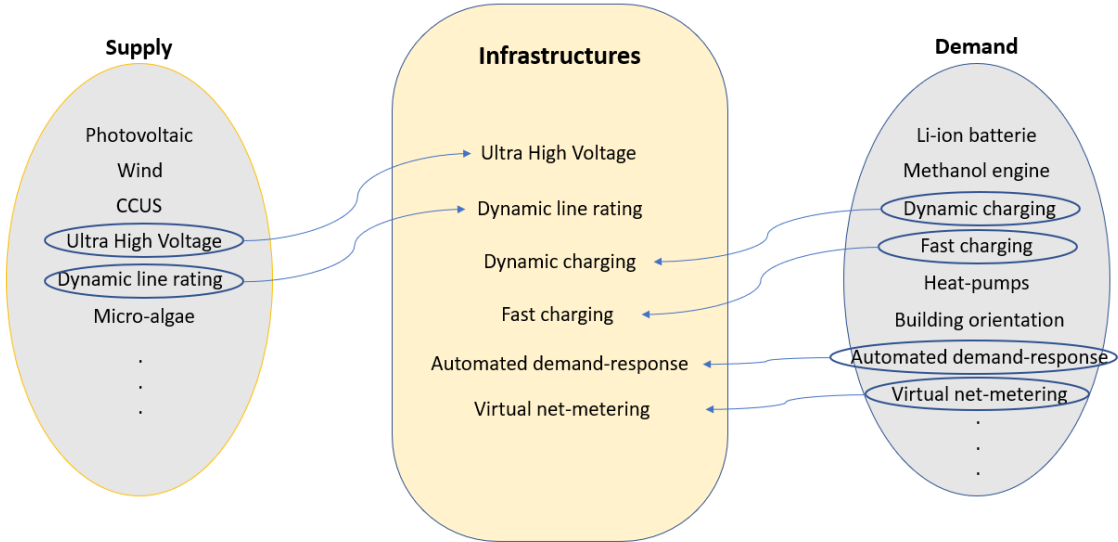


Figure 47 - Creation of an infrastructure-related technologies group

Table 8 shows that the new infrastructure group included 11 supply-side and 14 demand-side technologies (6.8% of the 368 technologies/components of the supply-side and demand-side groups). It is important to stress that the infrastructure group includes technologies/components related to energy transmission and storage (large storage systems), systems to charge means of transport, and the technologies required to integrate buildings and energy networks.

Figure 48 shows the weight of the new technologies’ groups after the infrastructure group’s creation. The infrastructures group represents just 6.8% of the total technologies/components present in the IEA database (25 of the 368 technologies).

The boxplot graph of Figure 49 compares the maturity level of the technologies/components of the new supply-side, demand-side and infrastructure groups. As can be concluded from that figure, the higher TRL for the Infrastructures group is 11, corresponding to *hydrogen pipeline* technology, the only one already in proven maturity. Seven technologies exist with a TRL of 9 (beginning of the dissemination stage). Five of those technologies are in the transport subsector (*dynamic and fast charging, hydrogen refuelling,*

magnetic levitation, and ammonia bunkering for shipping), one in the building’s subsector (double smart grids), and other in the supply side (tanker for ammonia transport). The hydrogen bunkering for shipping presents the lowest TRL (equal to 3). Most of the technologies are commercialisation-ready or at a higher stage of maturity.

Table 8 - Technologies included in the Infrastructure group

Infrastructures					
Side	Sector	Sub-Sector	Group	Technology	TRL
Supply	Power	Electrical grids	Integration	Virtual inertia/fast frequency response	5-7
			Transmission	Ultra-High Voltage HVDC	6
				Flexible HVDC grids	7
				Superconducting HVDC	6-7
				FACTS	8
				Dynamic Line Rating	8
	Distribution	Transactive energy	4		
	Other Fuel transformation	Hydrogen Transport		H2 pipeline	11
				Liquid H2 tanker	5
				LOHC tanker	5
		Ammonia Transport	Tanker	8-11	
Demand	Transport	Road	Infrastructure	Dynamic charging	9
				Dynamic charging	4
				Smart charging	5
				Fast Charging	9
				Hydrogen Refuelling	9
				Magnetic levitation	9
				Hyperloop	3-4
				Shipping	Infrastructure
	Ammonia Bunkering	9			
	Hydrogen Bunkering	3			
	Buildings	Digitalization	Grid interaction	Open automated demand response (OpenADR)	7
				Direct current building systems	8
				Double smart grids	9
Community Scale Solar - Virtual net metering				8	

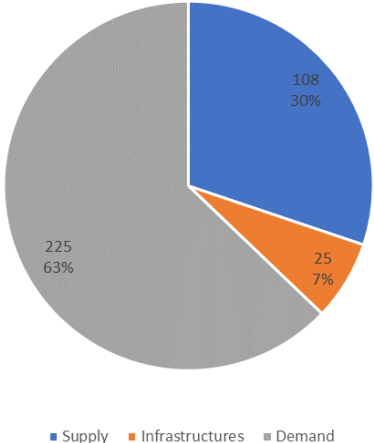


Figure 48 - Relative weight of Supply, Demand, and Infrastructures groups

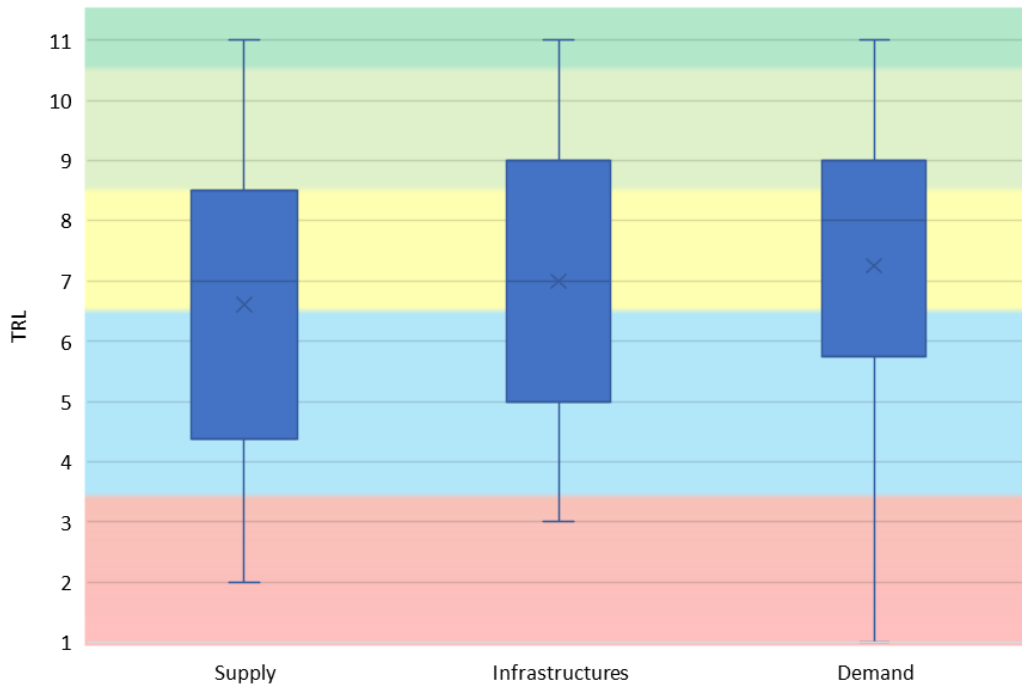


Figure 49 - Maturity of technologies for demand-side, supply-side and infrastructure groups

Table 8 also allows us to realise that the infrastructure technologies related to the supply side appear with a lower maturity level. Indeed, 50% of those technologies are in the prototype stage, while the remaining 50% are in the commercialisation-ready stage. The highest TRL equals 11, corresponding to the *hydrogen pipeline* technology. *Transactive energy* is the technology with the lowest TRL (TRL = 4). Concerning the infrastructure technologies related to the demand side, it is possible to conclude that 50% of those technologies present a TRL higher than 7. Most of those technologies are in the commercialisation-ready or dissemination states of maturity. However, no technologies have yet reached the state of proven technological maturity.

From a broader perspective, it becomes evident that technologies associated with the infrastructure sector have reached a level of maturity that aligns with the maturity levels of both demand-side and supply-side groups. Therefore, those technologies can support the faster and complete development of supply-side and demand-side technologies that depend on infrastructure technologies (e.g. the maturity of *microgrids* and *smart grid* technologies may influence the practical use of some *demand response* technologies, including intelligent appliances).

3.3.2. Supply-side technologies

The supply-side technologies considered (119) are divided into twelve segments, as shown in Figure 50. Note that three segments, concretely power generation, biofuel production and hydrogen production, represent almost three-quarters (72%) of all supply-side technologies.

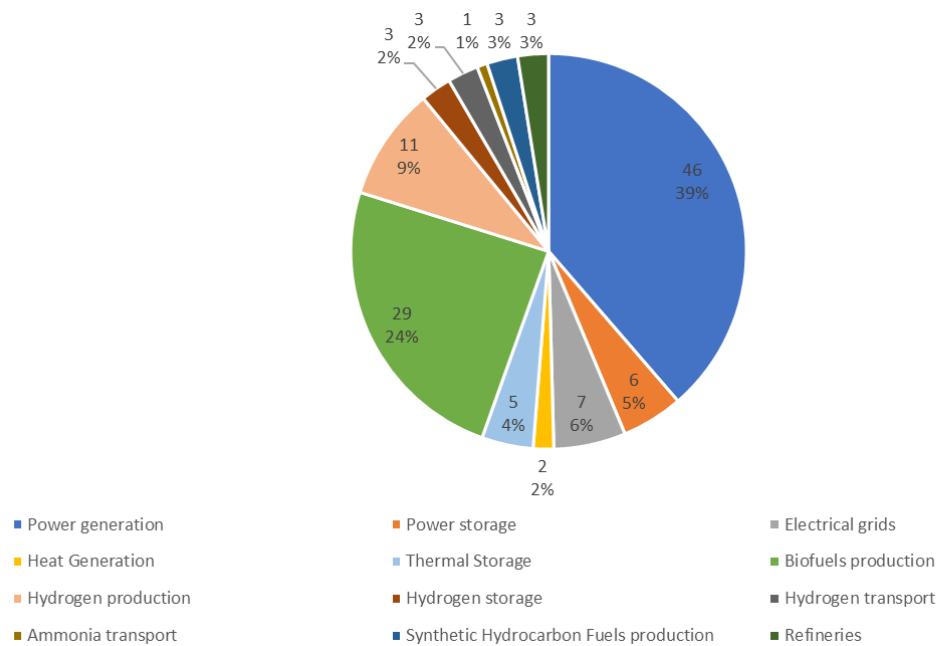


Figure 50 - Technologies included in each segment of the supply side

Table 9 analyses the maturity levels of the technologies within each segment. This kind of analysis was adopted due to the limited number of samples (technologies) in some segments, which could potentially impact the accuracy of the boxplot graph. Still, Figure 51 shows a boxplot graph for the items that include more than ten technologies.

Table 9 - Maturity assessment for the different segments of the supply side

Technological segment	TRL			Number of technologies			
	Max	Min	Median	TRL ≤ 6	6 < TRL ≤ 8	8 < TRL ≤ 10	TRL > 10
Power generation	11	2	7	21	12	9	4
Power storage	11	8	8.5	0	3	2	1
Electrical grids	8	4	6.5	3	4	0	0
Heat Generation	10	9	9.5	0	0	2	0
Thermal Storage	9	3.5	6	3	0	2	0
Biofuels production	9.5	3.5	6.5	14	9	6	0
Hydrogen production	9	3	6.5	5	3	3	0
Hydrogen storage	9.5	3	9.5	1	0	2	0
Hydrogen transport	5	11	5	2	0	0	1
Ammonia transport	9.5	9.5	9.5	0	0	1	0
Synthetic Hydrocarbon Fuels production	6.5	3.5	6	2	1	0	0
Refineries	5	3.5	3.5	3	0	0	0

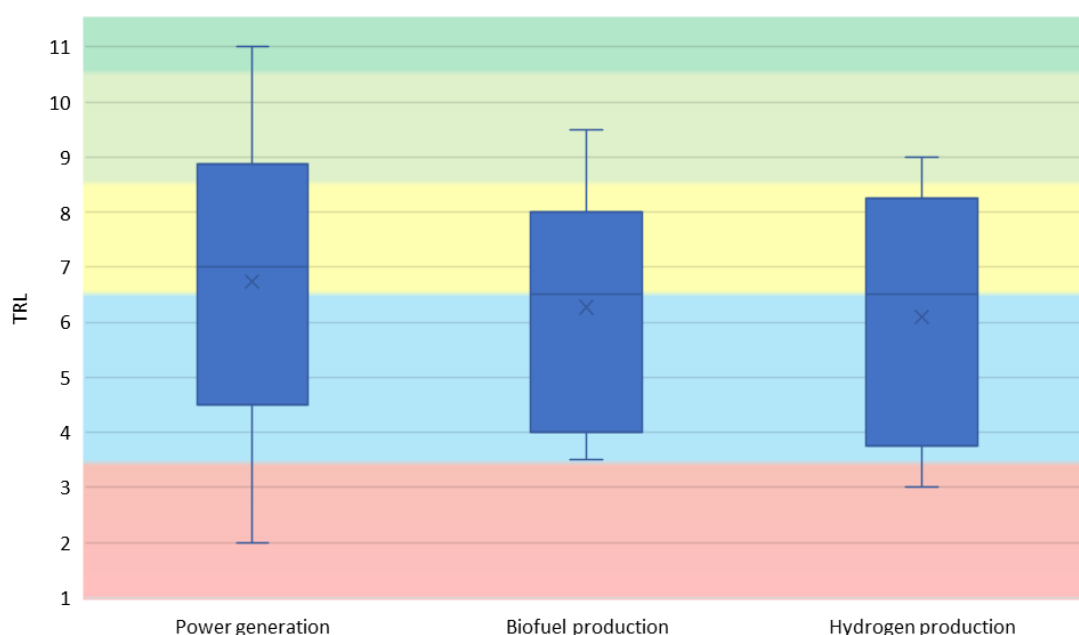


Figure 51 - Maturity of the technologies of some segments of the supply side

Power generation accounts for 39% of the supply-side technologies, corresponding to the largest segment. The technologies included in this segment present a high variability in the TRL value, with some technologies in the concept stage and others in the proven stage. Indeed, the technology with lower TRL (TRL = 1) is *nuclear fusion*, whereas the technologies with higher TRL (TRL = 11) are *hydropower*, *geothermal dry steam*, and *geothermal flash processes*. The median TRL value equals 7.

Six technologies are in the power storage segment, with a median TRL value of 8.5. Furthermore, all the technologies of this segment have either surpassed or are currently in the dissemination stage or above. The technologies with the lower TRL (TRL = 8) include *redox*

flow battery storage, smart inverters for battery storage, and compressed air energy storage. The *pumped storage* technology boasts the highest TRL value (TRL = 11).

The electrical grid segment also accounts for six technologies, with a median value of TRL equal to 6.5. The technology with lower TRL is *transitive energy distribution* (TRL = 4). The technologies with higher TRL (TRL = 8) are *flexible alternated current transmission systems (FACTS)* and *dynamic line rating*.

The heat generation segment is represented by only two technologies: *large-scale heat pumps* with a TRL = 9 and *solar thermal district heating* with a TRL = 10.

Five technologies are included in the thermal storage segment. The technology with a lower TRL (TRL = 3.5) is the *chemical reaction for thermochemical heat storage*, while the technology with the highest TRL (TRL = 9) is *ice storage for latent heat storage*. The median value of the TRL for those technologies equals 6.

Biofuel production is the second largest segment of the supply side, with twenty-nine technologies representing 24% of the total. The median value of TRL for those technologies equals 6.5. As shown in Figure 51, half of the technologies are only in the prototype stage of maturity. The technologies with lower TRL value (TRL = 3.5) are *microalgal hydrothermal liquefaction + upgrading for biodiesel, micro-algae and macro-algae (seaweed) anaerobic digestion for biogas* and *gasification + H₂ enhancement + fischer-tropsch for biodiesel*. The technologies with the highest TRL (TRL = 9.5) are *non-seaweed feedstock anaerobic digestion for biogas, sugar and starch from agricultural crops, enzymatic fermentation for bioethanol, fatty acid methyl ester (FAME) for biodiesel* and *hydrogenated vegetable oil (HVO) for biodiesel*.

Hydrogen production is the third largest segment with eleven technologies. The technologies with the lower maturity (TRL = 3) are *seawater electrolysis* and *chemical looping*. The technology with the highest maturity (TRL = 9) is *alkaline electrolysis*. The median TRL value for those technologies equals 6.5.

Hydrogen storage accounts only with three technologies: *salt cavern storage, storage tanks, and depleted oil & gas fields aquifers*. The first two technologies appear with a TRL = 9.5, and the last one with a TRL = 3.

Hydrogen transport also accounts for just three technologies: *H₂ pipeline* with the highest TRL value (TRL=11), *liquid H₂ tanker* (TRL = 5) and *liquid organic hydrogen carrier* (TRL = 5).

Ammonia transport only has one technology, the *tanker*, with a TRL value of 9.5.

Three technologies appear associated with the synthetic hydrocarbon fuel production segment: *methane from H₂ + CO₂* with a TRL of 6.5, *liquid fuels from H₂ + CO₂* with a TRL of 6 and *concentrating solar fuels* with a TRL of 3.5.

Finally, the refineries segment is also limited to three technologies: *post-combustion capture for process heaters*, *hydrogen production*, *post-combustion capture for fluid catalytic cracker*, and *oxy-fuel capture for fluid catalytic cracker*. The first two technologies have a TRL value of 3.5, and the last one has a TRL of 5.

3.3.3. Demand-side technologies

As previously referred, three sectors of demand-side technologies are considered by IEA: Industry, Transport and Buildings. Those sectors encompass 239 technologies: 73 in the Industry sector, 58 in the Transport sector and 108 in the Buildings sector. Figure 52 compares the maturity level for the technologies/components included in each sector. The buildings sector demonstrates the highest level of technological maturity, whereas the transport sector exhibits the lowest level. A more detailed analysis is done in the following sections.

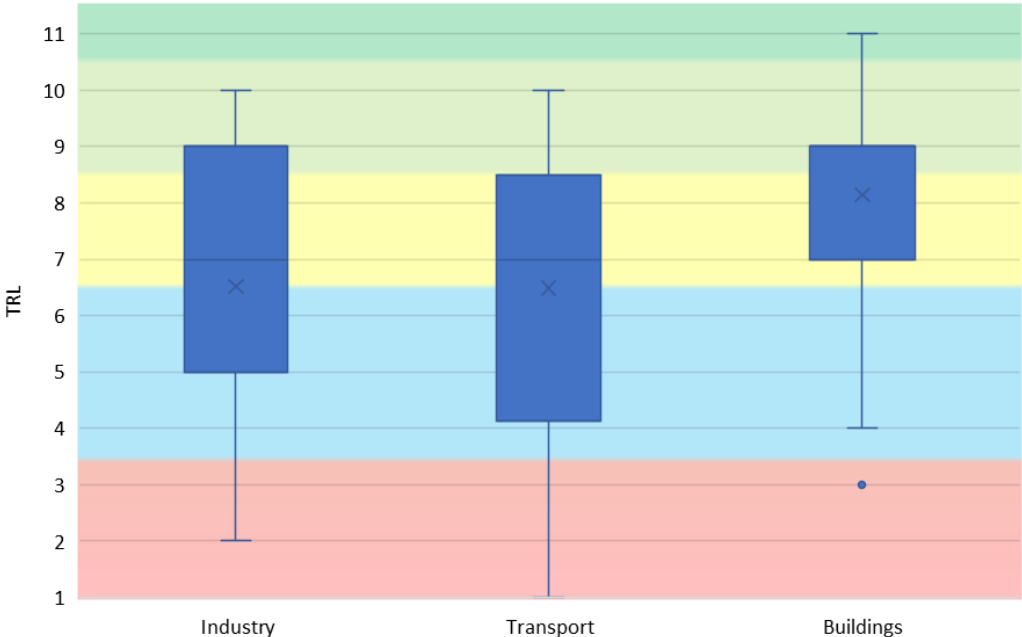


Figure 52 - Maturity of technologies by demand side sector

3.3.3.1. Industry sector

The technologies considered in this sector (73) are divided into seven segments: chemical industry, iron and steel industry, cement industry, pulp and paper industry, aluminium industry, material efficiency, and cross-cutting heating technologies. The last two segments may be understood as transversal technologies that can be used in different industrial processes and are not explicitly allocated to a specific industrial branch. Figure 53 shows the number of technologies included in each segment.

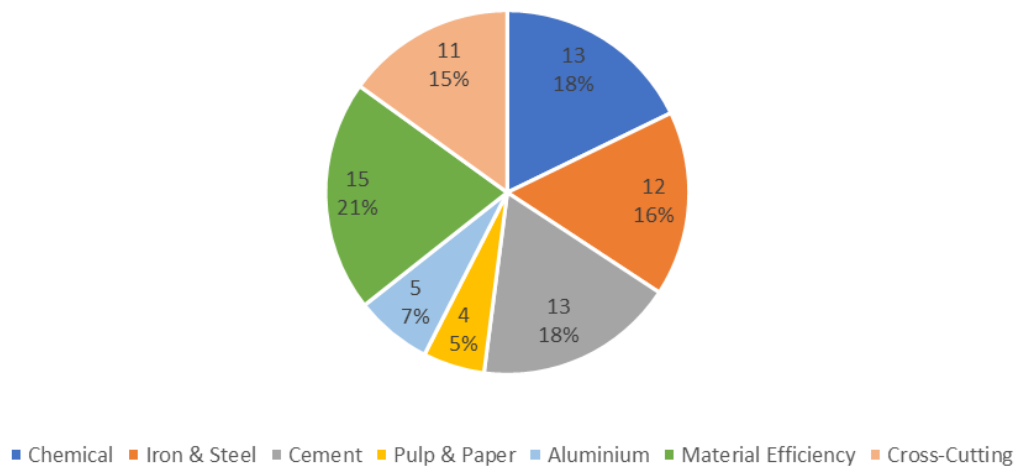


Figure 53 - Technologies included in each segment of the industry sector

Figure 52 shows that over 25% of the technologies considered in the industry sector are in the dissemination stage. Two technologies (*new recycling techniques for metal separation* and *induction heating for large-scale industrial heating processes*) have a TRL of 10, the highest TRL value in this sector. Those two technologies correspond to 2.7% of the total technologies considered in this sector (73).

Table 10 analyses the maturity levels of technologies within each segment mentioned earlier. This kind of analysis, as previously, was adopted due to a limited number of samples in each category, which could potentially impact the accuracy of the boxplot graph. Still, Figure 54 shows a boxplot graph for the items that include more than ten technologies.

Table 10 - Maturity assessment for the different segments of the industry subsector

Technological segment	TRL			Number of technologies			
	Max	Min	Median	TRL ≤ 6	6 < TRL ≤ 8	8 < TRL ≤ 10	TRL > 10
Chemical	9	3	7	4	6	3	0
Iron&Steel	8	3	5	9	3	0	0
Cement	9	3	7	6	5	2	0
Pulp&Paper	9	4	7	2	0	2	0
Aluminium	8	2	5	3	2	0	0
Material Efficiency	10	3	8	3	5	7	0
Cross-Cutting	10	3	6	6	0	5	0

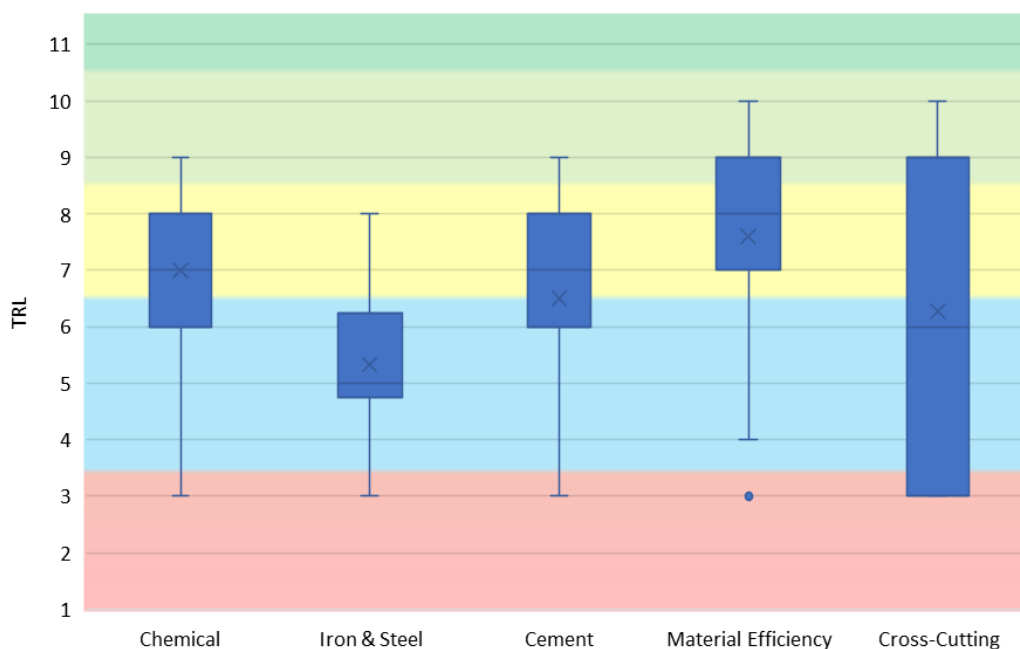


Figure 54 - Maturity of the technologies of some segments of the industry subsector

The Pulp and Paper industry presents only four technologies, two in the dissemination stage of maturity (*black liquor gasification* and *lignin extraction via precipitation and acidification*, both for bioenergy production). The technology with lower TRL, equal to 4, corresponds to *deep eutectic solvents*. The remaining technology, *lignin extraction via organic solvent*, presents a TRL of 5.

Concerning the Chemical Industry, which includes ammonia, methanol, and high-value chemical production, the technologies are mainly commercialisation-ready. *Carbon capture via chemical absorption* for ammonia production, *carbon capture by physical separation* for methanol production, and *fermentation* for ethylene production are the technologies with the higher TRL (TRL = 9), being in the dissemination stage. A total of nine technologies are in commercialisation-ready or higher stage of maturity. On the other hand, four technologies exist

in the prototype or concept definition stages (30.8% of the chemical technologies), where *steam cracker electrification* presents the lower TRL value (TRL = 3).

Regarding the Iron and Steel Industry, most technologies are still at the prototype level of maturity (75% of the 12 technologies). The higher TRL value (TRL = 8) corresponds to the *carbon capture by chemical absorption* to direct reduced iron. Three technologies (25%) are in that maturity stage (commercialisation-ready and above). *The smelting reduction based on hydrogen plasma* technology appears with a lower TRL value (TRL = 3).

The *CO₂ sequestration in inert carbonate materials (mineralisation)* and *calcined clay for alternative cement constituents* present the highest TRL (TRL = 9) among the technologies included in the Cement Industry. A total of 53.8% of this item's technologies (7 in 13 technologies) are in the commercialisation-ready or dissemination stages of maturity. Conversely, 46.2% of the technologies are in the prototype or lower maturity stage. The *magnesium oxides derived from magnesium silicate (MOMs)* technology present the lowest TRL value (TRL = 3).

The Aluminium Industry item only includes five technologies, two in the commercialisation-ready stage of maturity (*inert anodes* for primary smelting and *aluminium smelter demand response through integration of heat exchangers to vary energy consumption and production levels*). The *carbon capture and storage* for the aluminium smelter is the technology with the lowest TRL (TRL = 2). The *fuel switching or electrification of the bayer process* for alumina refining and *multipolar cells* for primary smelter technologies are in the prototype stage of maturity.

Material efficiency and Cross-cutting are more transversal since they are not dedicated to one specific type of industry (instead, they are related to some processes). Concerning Material efficiency, 80% of the technologies are in the commercialisation-ready stage (5 technologies) or the dissemination stage (7 technologies). The *novel physical separation for metals* is the technology with the higher TRL (TRL = 10). 20% of technologies are still in the prototype (2 technologies) and the concept definition (1 technology) stage of maturity. The least mature technology is the *Folding-shearing* for reducing metal forming losses, with a TRL = 3.

Cross-cutting technologies concern heating processes. The technologies related to low-temperature heating have, in a general way, the highest TRL values. The exception is the *induction technology (high-temperature heating)*, which presents the highest TRL value (TRL = 10). Indeed, almost all high-temperature heating technologies appear in the concept stage of

maturity (*ultra-violet, radio wave, infrared, electric arc and plasma arc furnaces* applied to new applications). Looking at these technologies as a whole, we can conclude that 45.5% are in the dissemination stage. On the other hand, 55.5% of the technologies are in the prototype stage (2 technologies) or the concept definition stage (4 technologies).

3.3.3.2. Transport sector

A significant part of the technologies in this sector is related to the electrification of the means of transport. Indeed, 24.1% of the 58 technologies concern pure electric vehicles. This percentage increases to 37.9% and 46.6% if fuel cell-based vehicles and charging technologies are considered.

As seen in Figure 52, almost 25% of the 58 technologies of the Transport sector (11 technologies) are still in the definition of concept stage. The *Li-air* battery has the lowest TRL value (TRL = 1). On the other hand, nearly 25% of the technologies are in the dissemination stage, and no technologies in the proven stage exist. The *rubber bulb for shipping*, with TRL = 10, is the technology with a higher level of maturity. The transport sector is the one that presents the higher variability of TRL values. More than 50% of the 58 technologies are in the commercialisation-ready or dissemination stages of maturity.

The transport sector may be subdivided into four segments: road, rail, shipping, and aviation. Figure 55 shows the percentage of innovative technologies encompassed by each segment.

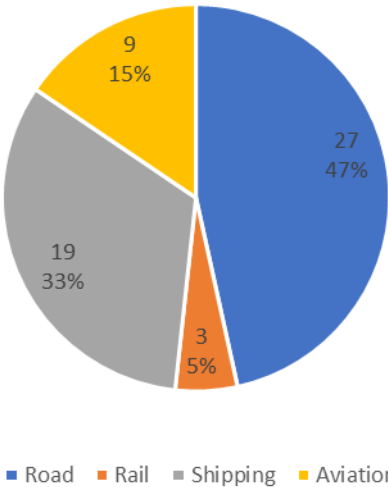


Figure 55 - Technologies included in each segment of the transport sector

Table 11 analyses the maturity level of technologies included in each segment. Once again, this kind of analysis was adopted because of the low number of samples (technologies) in some segments, which may influence the results of a boxplot graph. Still, Figure 56 shows a boxplot comparing the maturity of the technologies included in the road and shipping segments.

Table 11 - Maturity assessment for the different segments of the transport subsector

Technological segment	TRL			Nr of technologies			
	Max	Min	Median	TRL ≤ 6	6 < TRL ≤ 8	8 < TRL ≤ 10	TRL > 10
Road	9	1	8.5	12	0	15	0
Rail	8	7	7	0	3	0	0
Shipping	10	3	7	7	7	7	0
Aviation	7.5	3	3.5	7	2	0	0

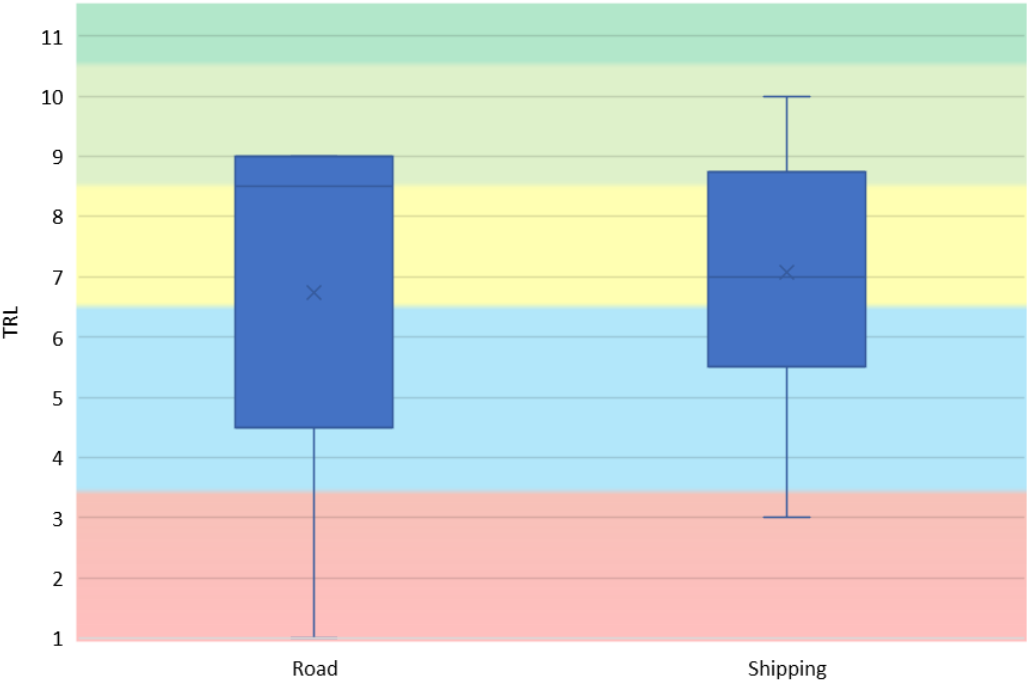


Figure 56 - Maturity of the technologies of some segments of the transport subsector

The information presented in Table 11 evidences that the maturity of the technologies included in the Aviation segment are the least mature, with just two in the commercialisation-ready stage (*geared turbofan ultra-high bypass ratio (UHBR) engine* and *electric taxiing*). The technologies related to hydrogen aircraft and some related to design are in the concept definition stage of maturity.

Concerning the rail segment, only three technologies exist, all in the commercialisation-ready stage. The *batterie operated trains* have a TRL = 7, *hydrogen fuel cell trains* a TRL of 8, and *hybrid trains* a TRL = 7.

Figure 56 shows that the road segment's technologies present higher variability in the TRL values than shipping technologies. The *Li-air* battery technology for use with electric vehicles has the lowest value of TRL (TRL = 1). On the other side, eight technologies with TRL = 9 exist (the higher TRL), meaning that 30% of all road technologies are in the dissemination stage. These technologies are related to *Li-ion batteries*, *fuel cells*, and *biogas*; some are related to the infrastructures. Twelve technologies (44.4% of the total road technologies) are at the prototype or concept definition stages of maturity.

Regarding shipping technologies, five technologies (corresponding to 26.3% of the 19 technologies included in this segment) are in the commercialisation-ready stage of maturity. The *rubber bulb* technology presents a higher TRL (TRL = 10), meaning that this technology is at the dissemination stage. Four other technologies are also in the dissemination stage. The lower TRL value (TRL = 3) corresponds to *hydrogen bunkering technology*, which is at the concept stage of maturity.

3.3.3.3. Buildings sector

According to Figure 52, the building sector's technologies present a higher maturity level, mainly due to heat and cooling technologies and building design, which show higher TRL values. The median value for the TRL equals 9. Moreover, 25% of the technologies are in the dissemination stage, and 6.5% (7 technologies) are already proven technologies, with a TRL value of 11 (mainly heat and cooling technologies and building design procedures). Some outliers, three with TRL of 3 (corresponding to less than 3% of the technologies), may be found in the figure, which refers to the *integrated heat pump with storage*, *quad-generation*, and *direct current lighting technologies*.

The technologies included in the Buildings sector may be split into eight segments, as shown in Figure 57. This figure shows us that almost three-quarters (72%) of the technologies/components considered for the building sector are related to heat and cooling, building envelope, and system integration segments.

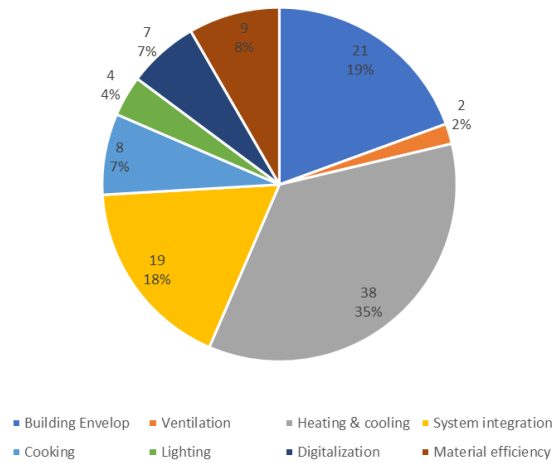


Figure 57 - Technologies included in each segment of the buildings sector

Table 12 analyses the maturity level of technologies included in each segment. Figure 58 shows a boxplot comparing the maturity of technologies in the three most relevant segments (heat and cooling, building envelope, and system integration). The remaining segments were not included in this graph due to their low number of technologies, which may influence the boxplot results.

Table 12 - Maturity assessment for the different segments of the buildings subsector

Technological segment	TRL			Nr of technologies			
	Max	Min	Median	TRL ≤ 6	6 < TRL ≤ 8	8 < TRL ≤ 10	TRL > 10
Building Envelope	11	4	8	4	10	5	2
Ventilation	11	9	10	0	0	1	1
Heating&Cooling	11	3	9	7	10	20	1
System Integration	11	3	8	2	9	7	1
Cooking	11	9	10	0	0	6	2
Lighting	10	3	9	1	0	3	0
Digitalisation	9	7	8	0	4	3	0
Material efficiency	10	4	9	2	1	6	0

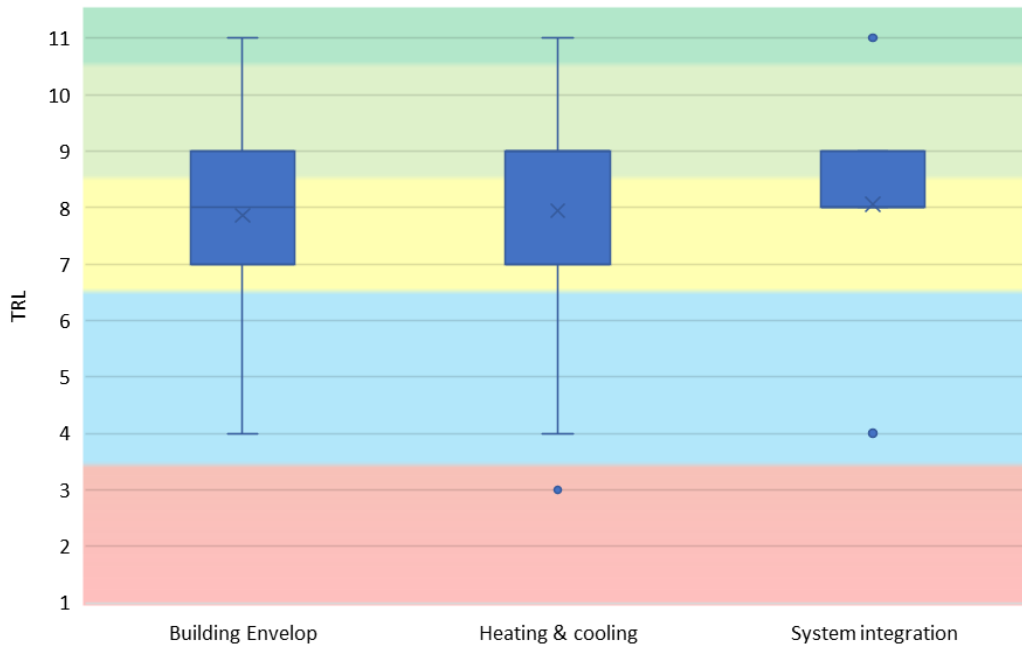


Figure 58 - Maturity of the technologies of some segments of the buildings subsector

As previously referred, the technologies included in the Buildings sector are the ones that present a higher level of maturity. In particular, the technologies of the building envelope segment have a median TRL equal to 8. A total of 17 technologies (81% of this segment) are commercialisation-ready or have a higher level of maturity. The *building orientation* (for thermal and lighting needs) has a higher TRL value (TRL = 11), meaning that it is already in the proven stage of maturity. A total of 7 technologies (33.3%) have TRL > 8, meaning they are commercialisation-ready or at a higher level of maturity. Even so, 47.6% of the technologies present TRL < 6, but all are in the prototype stage of maturity. The *breathing wall* is the technology with the lower TRL value (TRL = 4).

The level of maturity of technologies in the heating and cooling segment is comparable to that of the building envelope segment. The majority of technologies, approximately 81.6%, are either at the stage of being ready for commercialization or have reached an even higher level of maturity. The technology related to heating and cooling *biomass heaters* stands out with a TRL value of 11, indicating an exceptionally high level of maturity. Nevertheless, seven technologies (18.4%) are still in the prototype stage of maturity. The *integrated heat pump with storage* for cooling and heating is the technology with the lowest TRL (TRL = 3), remaining in the concept definition stage of maturity.

System integration is another segment that includes technologies with a higher maturity level. Indeed, 89.5% (17) of the technologies are commercialisation-ready or have a higher

level of maturity (TRL > 8). *Thermal storage via hot water tanks* has a higher TRL (TRL = 11), meaning it is a proven technology. On the other hand, 10.5% of the technologies are in the prototype stage of maturity. The *quad-generation* technology presents the lowest TRL value (TRL = 3).

All the technologies in the cooking segment are already in the dissemination or proven technologies stages of maturity. The *induction* and *vitroceramic stoves* present the highest TRL (TRL = 11), while *solar cooking* has the lowest TRL value (TRL = 9).

Regarding the lighting segment, just one of the four technologies is in the concept stage of maturity, concretely the *direct current lightning*, with a TRL = 3. The remaining technologies are *conventional LED* with a TRL = 10, *OLED* with TRL = 9, and *PLED* with TRL = 9.

Most of the technologies included in the digitalisation segment are in the commercialisation-ready stage (42.9% of 7 technologies). The highest TRL value (TRL = 9) corresponds to *advanced lighting control systems*(*dimmiability* and *occupancy sensors*), *smart thermostats*, and *double smart grid technologies*. The *open automated demand response* (*OpenADR*) technology has the lowest TRL value (TRL=7). The *gamification devices*, *direct current building systems*, and *community-scale solar virtual net metering* have a TRL = 8.

The ventilation segment only contains two technologies: *dual flow ventilation* with TRL = 9 (dissemination stage of maturity) and *natural ventilation* with TRL = 11 (proven technology).

In conclusion, from a global view of the building sector, it is possible to understand that a significant part of the technologies is commercialisation-ready or at a higher maturity level. Indeed, of the 108 technologies included in this sector, 6.5% are proven technologies, 47.2% are in the dissemination stage, and 31.5% are in the commercialisation-ready stage of maturity.

3.3.4. Maturity of carbon capture technologies

The carbon capture technologies may be split into two groups:

- the negative emissions technologies, which are devoted to the capture of existing atmospheric CO₂.
- the avoided emissions technologies that relate to the carbon capture and storage (CCS) facilities used with other processes (e.g., electricity generation in a natural gas-fired power plant) to capture the emissions generated by these processes.

Both groups' technologies are devoted to mitigating CO₂ consequences but use different approaches (removing already existent CO₂ in the case of negative emissions technologies or reducing the emissions to the atmosphere in the case of avoided emissions technologies). This work assumes that demand-side and supply-side technologies (previously referred groups – section 3.2) are avoided emissions technologies if they include carbon capture and storage systems. The ten technologies incorporated into the CO₂ infrastructures group mentioned in section 3.2 belong to the negative emissions technologies group. Figure 59 shows each group's relative number of carbon capture technologies.

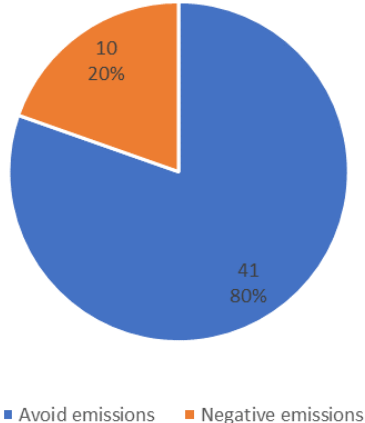


Figure 59 - Technologies included in each group of the carbon capture technologies

Figure 60 shows a boxplot comparing the maturity level of the technologies integrated into avoided and negative emissions technologies. It is important to stress that the few technologies in the negative emissions group may produce some misinterpretations. Even so, the graph supports that the negative emissions technology appears slightly more mature than avoided emissions technologies.

Concerning the ten technologies included in the negative emissions group, 60% (6 technologies) have TRL equal to or higher than 7, meaning that those technologies are at a commercialisation-ready or higher stage of maturity. However, only three technologies are in the dissemination stage, with TRL = 9: the *pipeline for CO₂ transport*, *saline formations* and *CO₂-EOR for storage*. The lowest TRL (TRL = 3) is *mineral storage*.

Regarding the avoided emissions group, 57.9% of the technologies (22) are in a commercialisation-ready or higher stage of maturity, while 42.1% are still in the prototype (14 technologies) or concept definition (2 technologies) stages of maturity.

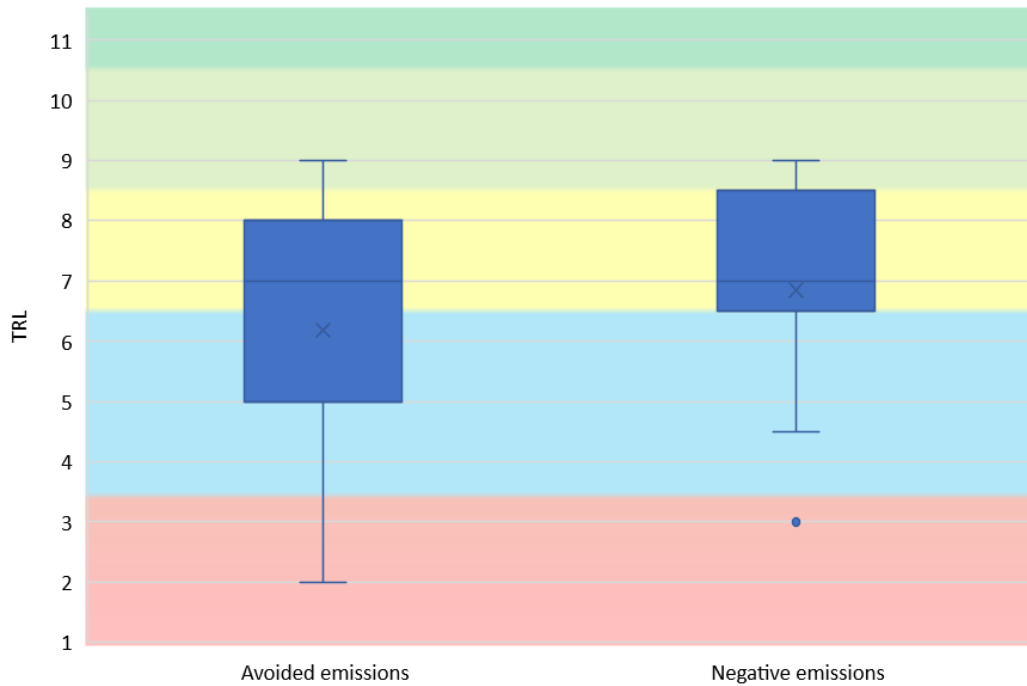


Figure 60 - Maturity of each group of carbon capture technologies

The avoided emissions technologies may be found in the set of technologies corresponding to the supply-side group mentioned in section 3.3.2 and in the set of technologies of the industry sector of the demand-side group mentioned (section 3.3.3.1). Figure 61 shows the percentage of CCS-based technologies of each referred set.

Figure 62 shows a box plot graph comparing the maturity of the avoided emissions technologies used in the supply-side and demand-side (Industry) groups. As may be realised by the chart, more than 50% of the supply-side technologies have a $TRL \geq 7$, meaning that they are at a commercialisation-ready or higher stage of maturity. Moreover, the variance in the TRL values for those technologies is lower than the one verified for the Industry case.

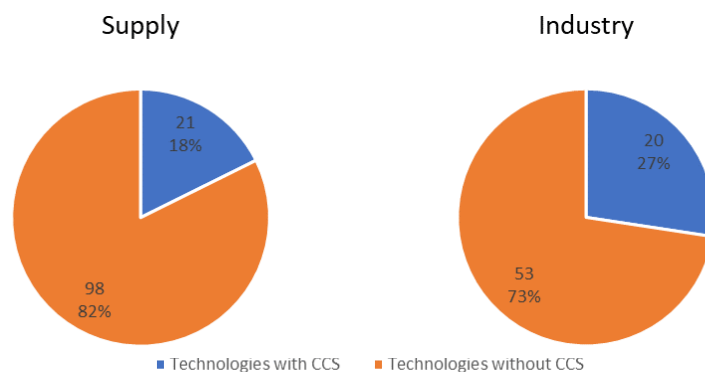


Figure 61- Number of avoided emissions technologies according to the side they belong to (supply/demand)

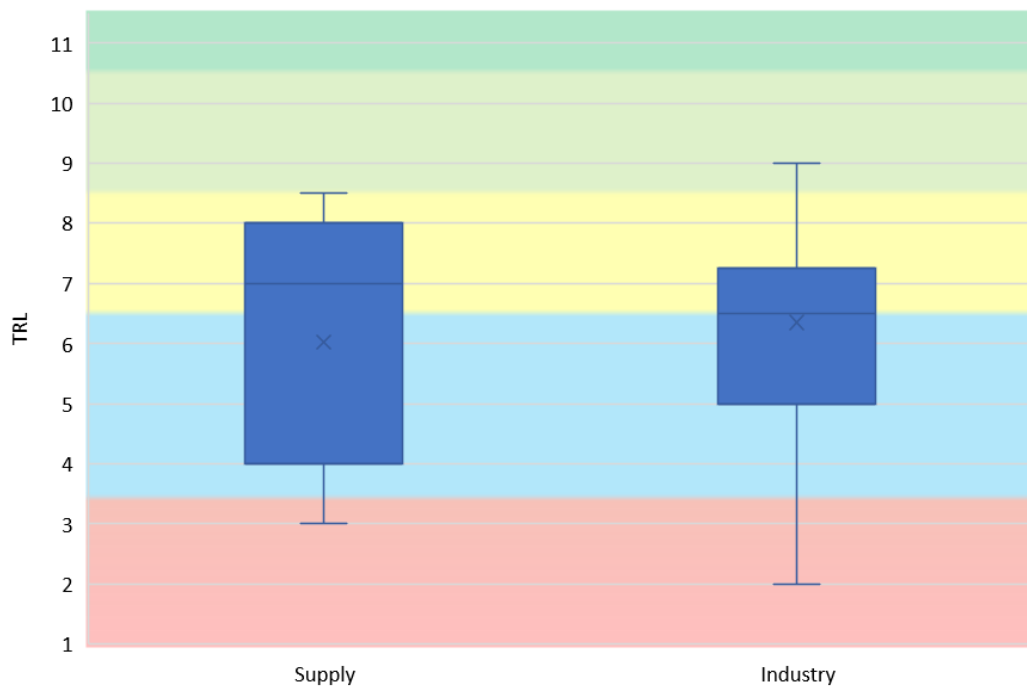


Figure 62 - TRL of avoided emissions technologies according to the side they belong to (demand/supply side)

The higher TRL value for the case of supply-side technologies is $TRL = 8.5$, corresponding to *fossil-derived hydrogen production* technology. Conversely, *power production through biomass* presents the lowest TRL value ($TRL = 3$). Note that 47.6% of the supply-side technologies are yet in the prototype or lower stage of maturity (19% in the concept definition stage). On the supply side, the most mature technologies that use CCS belong to technologies regarding *post-combustion/chemical* processes. At the same time, the least evolved is regarding *pre-combustion* for biomass applications, *coal gasification* related to hydrogen production, and processes regarding refineries.

On the industry side, the most mature technologies that use CCS are related to ammonia and methanol production, with $TRL = 9$, meaning that they are already in the dissemination stage of maturity. A total of ten technologies (50%) are still in the prototype stage of maturity, and the other ten are in the concept definition stage. The CCS technology for the *aluminium smelter* has the lowest TRL value ($TRL = 2$).

3.3.5. Maturity of the technologies according to their granularity

In this section, the maturity of the technologies, considering their granularity, is assessed.

Granularity may be defined as a measure of how divisible a system is. For example, due to techno-economical reasons, a nuclear power plant has an installed power exceeding several MW or GW. Therefore, it is not considered a granular technology but a lumpy technology. On the other hand, photovoltaic (PV) technology is granular because we can have a PV system with just a few kW (and even lower) installed powers. However, this does not hinder the possibility of having a photovoltaic power plant with higher values of installed capacity (e.g. in the MW range). Therefore, a granular technology may also be seen as one that increases system capacity and performance through incremental expansion.

Figure 63 shows the maturity of the supply-side group of technologies according to their granularity. The analysis is based on a literature review work ([53] – [75]) that allowed us to understand the granularity of those technologies. Three power ranges were assumed in the analysis: $P \leq 100$ kW, 100 kW $< P < 1$ MW and $P \geq 1$ MW, as shown in Table 13.

Table 13 - Number of technologies according to the granularity

Granularity	Number of supply-side technologies
$P \leq 100$ kW	30
100 kW $< P < 1$ MW	29
$P \geq 1$ MW	60
Total	119

The graph in Figure 63 shows that more granular technologies have higher TRL values, that is, higher maturity. The technologies with $P \leq 100$ kW have a median TRL of 8.25, and 50% are in dissemination or at a higher stage of maturity. Almost 74% of the technologies are commercialisation-ready or have a higher level of maturity (including photovoltaic, solar thermal, and battery storage, among others). The higher TRL value is 11, corresponding to *hydropower*. The *thermoelectric heat storage by chemical reaction* with TRL = 3.5, *photovoltaic using perovskite solar cells* with TRL = 4, and two technologies related to hydrogen transportation (*liquid tanker* and *LOHC tanker*), with TRL = 5, have the lower stage of maturity, corresponding to the prototype stage.

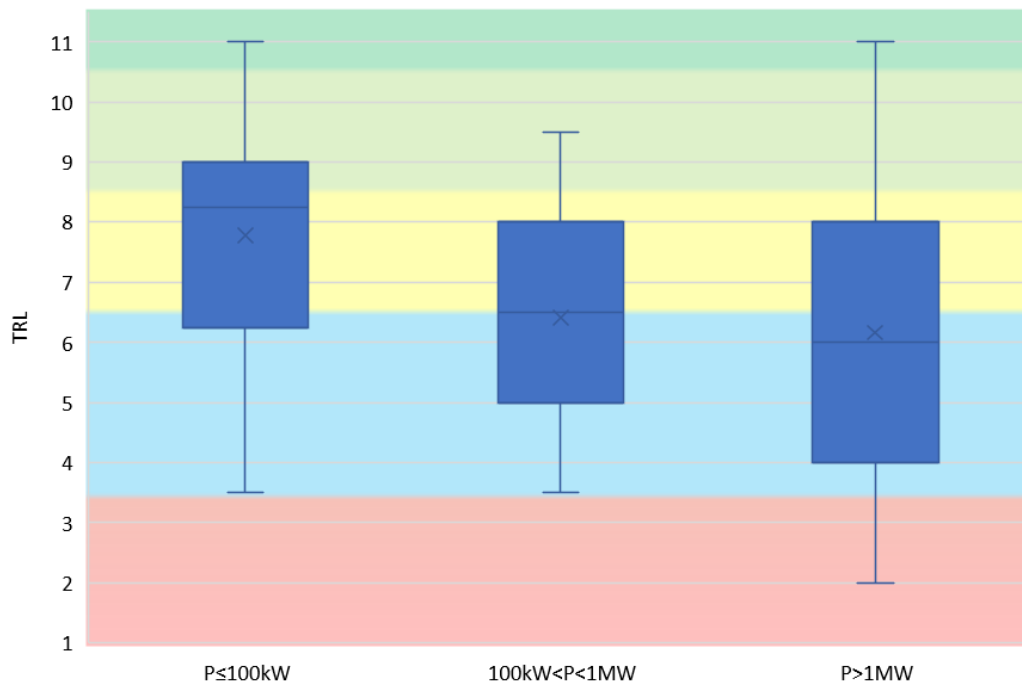


Figure 63 - TRL by granularity for the supply side

The technologies with granularity in the range $100\text{ kW} < P < 1\text{ MW}$ have a median TRL of 6.5, which is lower than the one of the technologies with $P \leq 100\text{ kW}$. In this case, 51.7% of the technologies are commercialisation-ready or have a higher level of maturity, while 48.3% stay in the prototype (44.8%) or concept definition (3.4%, only one technology) stages of maturity. The higher TRL value (TRL = 9.5) is achieved by *enzymatic fermentation* for bioethanol production and biodiesel production two technologies (*fatty acid methyl ester (FAME)* and *hydrogenated vegetable oil (HVO)*). The *gasification + H₂ enhancement + fischer-tropsch (H₂ BTL)* for biodiesel production presents the lower TRL, with TRL = 3.5, meaning that this technology is at the prototype level of maturity.

Concerning technologies with $P \geq 1\text{ MW}$, Figure 63 evidences a higher variability in TRL values, ranging from 2 to 11. The median for the TRL value is 6, and 53.3% of the technologies are in the prototype or lower stage of maturity. *Nuclear fusion* appears as the technology with the lower TRL value (TRL = 2), staying in the concept definition stage of maturity. The more mature technologies correspond to the power production *from geothermal via dry steam or flash process*, the *mechanical storage of energy via flywheel*, and the *H₂ pipeline*, with TRL = 11, which is in the proven stage of maturity. A total of four technologies (6.6%) are already proven, while ten technologies (16.7%) are in the dissemination stage of maturity. Note that 46.7% of the technologies are commercialisation-ready or have a higher level of maturity, which is related to many power generation technologies (fission-based

nuclear, geothermal, coal, etc.), biodiesel production, and hydrogen production, among others, included in this group.

Concerning the demand-side group, the granularity is more homogeneous. Indeed, the technologies of the Industry sector are essentially lumpy ($P \geq 1\text{MW}$), while the technologies of the Transport and Buildings sectors appear more granular ($P \leq 100\text{kW}$).

3.3.6. Maturity of technologies by energetic vector

This section introduces a maturity assessment for technologies according to the energy vector they belong to. Following the definition presented in [76], an energy vector is assumed to be a tool that allows energy transportation and/or storage. Figure 64 allows a better understanding of this concept. In this scenario, there are two energy vectors: hydrogen and electricity. Hydrogen is the energy vector for pyrolysis technology, while electricity is the energy vector for fuel cell technology. However, when both the pyrolysis and fuel cell processes are components of a comprehensive technology for electricity generation based on pyrolysis, it is important to recognize that electricity is the primary energy carrier. In this context, electricity acts as the vector that delivers energy to its ultimate destination for consumption.

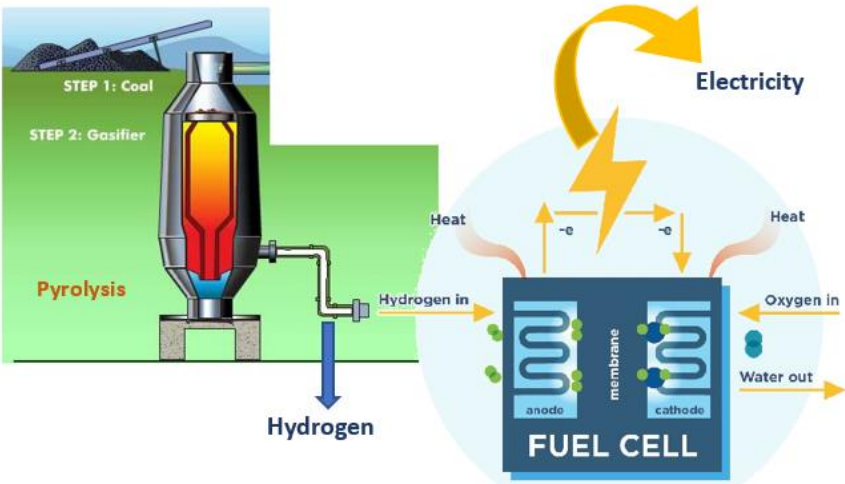


Figure 64 - Concept of energy vector

Six energy vectors were considered in the analysis done in this work:

- electricity;
- hydrogen;
- biofuels;
- synthetic fuels;
- fossil fuels;
- heat.

At this point, it is essential to make two clarifications. The first one has to do with hydrogen, which, in the literature, is considered a synthetic fuel since it doesn't exist in an isolated form in nature (and thus needs to be produced). However, hydrogen is assumed separately in this work because of the current big bet in this energy vector. The IEA also takes this energy vector as separated from synthetic fuels. The second clarification is related to the fact that not all of the 368 technologies listed by IEA were considered in this analysis since some technologies do not produce any energy vector.

Figure 65 shows the number of supply-side and demand-side technologies related to the energy vectors. As understood, the total number of technologies of the supply-side group is considered, while just 177 technologies (74.1%) of the demand-side group are included. Note that the number on the chart in Figure 65 for the demand side group doesn't add up to 177. That is because some technologies can have more than one energy vector, such as, for example, a hybrid vehicle (where electricity, fossil fuels, or synthetic fuel vectors may be considered). Moreover, the charts in Figure 65 allow us to conclude that electricity is the more relevant energy vector in the supply-side group of technologies. The electricity and biofuel vectors represent almost three-quarters of the technologies in this group. The hydrogen vector appears as the third most relevant, with 15% of the technologies related to it.

Concerning the demand side, it is clear that the heat vector is the more relevant, followed by electricity. The synthetic fuels vector also appears to have a higher relevance. Those three energy vectors together account for 83% of demand-side group technologies. The hydrogen-related technologies are the fourth more relevant set.

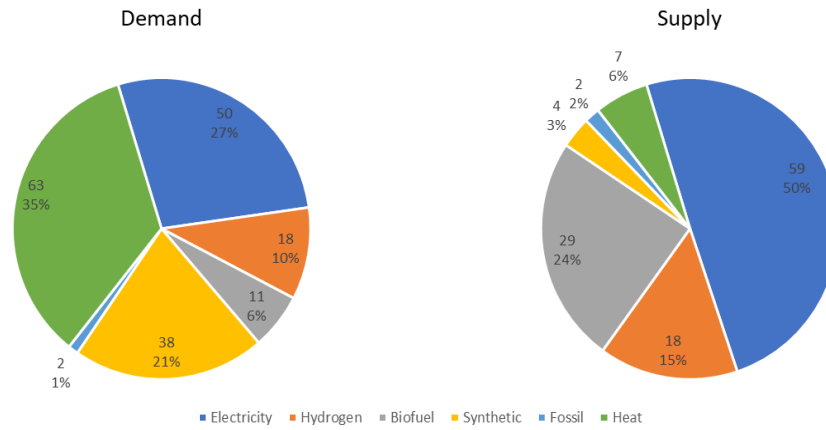


Figure 65 - Division of the vectors by side

Table 14 shows an analysis of the maturity level of technologies considering their separation on the supply or demand side and by energy vector. Figure 66 shows a boxplot comparing the maturity of the technologies related to the most relevant energy vectors. The remaining subsectors were not included in this graph due to their low number of technologies, which may influence the boxplot results.

Table 14 - Maturity assessment by energy vector

Group	Energy vector	TRL			Nr of technologies			
		Max	Min	Median	TRL ≤ 6	6 < TRL ≤ 8	8 < TRL ≤ 10	TRL > 10
Supply-side	Electricity	11	2	7	24	19	11	5
	Hydrogen	11	3	6.25	9	3	5	1
	Biofuels	9.5	3.5	6.5	14	9	6	0
	Synthetic fuels	9.5	3.5	6.25	2	1	1	0
	Fossil fuels	5	3.5	4.25	2	0	0	0
	Heat	10	3.5	8.5	3	0	4	0
Demand-side	Electricity	11	1	8.25	18	7	23	2
	Hydrogen	9	3	6	10	3	5	0
	Biofuels	10	5	9	1	1	9	0
	Synthetic fuels	9	3	7	16	15	7	0
	Fossil fuels	10	7	8.5	0	1	1	0
	Heat	11	3	8	13	21	27	2

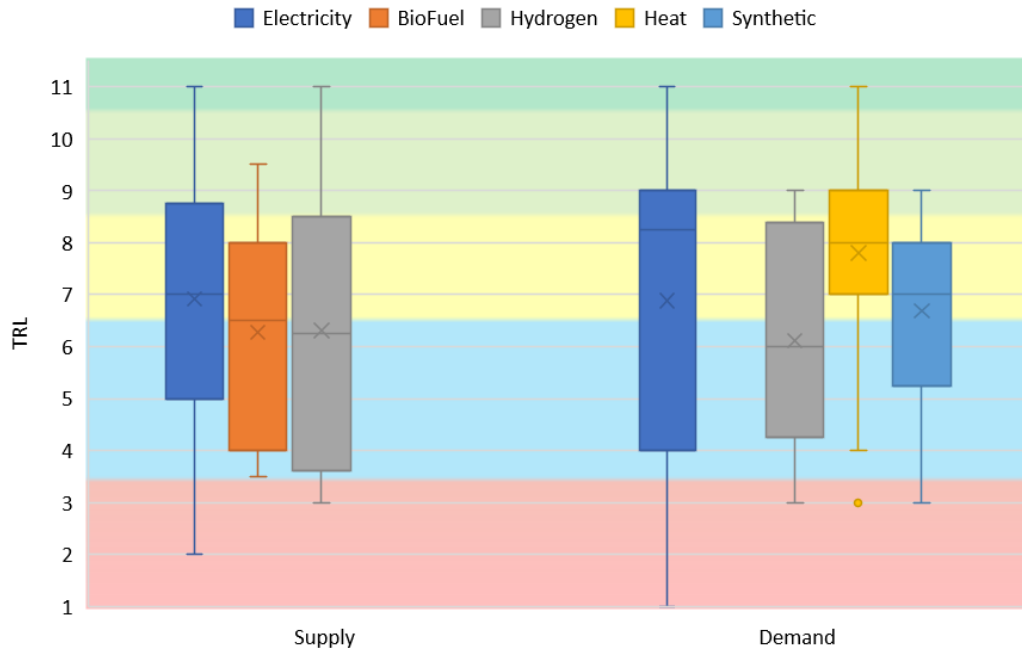


Figure 66 - TRL of technologies according to the energy vector and side (supply or demand)

Figure 66 and Table 14 show that the technologies on the demand side related to the electricity vector have a more significant maturity variation than those on the supply side. Nevertheless, 40.1% of the demand side and 24.3% of the supply side technologies are at the dissemination or a higher level of maturity. A total of five technologies on the supply side have a TRL = 11, including *hydropower*, *geothermal (dry steam and flash process)*, *pumped storage*, *H₂ pipeline*. Four demand-side technologies also have TRL = 11: *biomass heaters (trough wood-burning stoves)*, *hot water tanks (for heat storage)*, *high-efficiency induction cooking*, and *electric stoves*. Therefore, a total of six technologies (2.1%) related to the electric vector are already in the proven stage of maturity.

Regarding the lower level of maturity, almost 25% of the technologies on the demand side are in the concept stage only. The *Li-air battery* has the lowest TRL value (TRL = 1). On the supply side, *nuclear fusion* has the lowest TRL (TRL = 2), being that 49 of the technologies are still in prototype or at a lower level of maturity. Finally, it is important to stress that 54.6% of the supply-side (65) and 64.4% of the demand-side (114) technologies are commercialisation-ready or have a higher level of maturity.

Concerning the hydrogen vector, the maturity is similar between the supply and demand technologies but still has an advantage for the demand side. Indeed, 50% of supply-side and 72.2% of demand-side technologies are commercialisation-ready or have a higher level of maturity. Therefore, almost 61.1% of all hydrogen-related technologies are in those maturity

stages. The *H₂ pipelining* is the supply-side technology with the highest TRL value, corresponding to TRL = 11, meaning it is already a proven technology. For the demand side, the *fuel-cell vehicle* and the *hydrogen refuelling* have the highest TRL value (TRL = 9).

Moreover, the supply and demand sides have technologies in the dissemination stage of maturity, five in each. A total of 19 technologies (52.8% of all hydrogen-related technologies) are still in the prototype or concept definition stages of maturity. The lowest TRL value is 3, which happens for technologies from the supply side (*seawater and chemical looping electrolysis for hydrogen production* and *depleted oil and gas fields aquifers for hydrogen storage*) and the demand side (*hydrogen bunkering for shipping* and *smelting reduction based on hydrogen*).

For biofuels-related technologies, it is possible to conclude, based on Table 14, that demand-side technologies have a higher maturity level. A total of 3.6% of the technologies (4) included in the demand-side group have TRL = 10, meaning they are in the dissemination stage of maturity. Those technologies mainly relate to the Buildings sector, including *domestic biogas digesters* and *cooking stoves*. Regarding the supply side, just 20.7% of the technologies (6) are in the dissemination stage of maturity, mainly related to biodiesel, biogas, and bioethanol production (*anaerobic digestion*, *enzymatic fermentation*, *fatty acid methyl ester*, and *hydrogenated vegetable oil*). On the supply side, 50% of the technologies are in the prototype stage of maturity, where *biogas production from micro-algae (anaerobic digestion)* and *biodiesel production (gasification + H₂ enhancement + fischer-tropsch (H₂ BTL) and hydrothermal liquefaction plus upgrading)* is the technology with the lowest TRL (TRL = 3.5). On the demand side, *lignin extraction through organic solving for waste product conversion to chemicals and bioenergy* in the industry of pulp&paper (TRL = 5) and *gas hybrid train* (TRL = 7) have lower values of TRL.

Regarding synthetic fuel energy vector, it is important to stress that most technologies are included in the demand-side group (90.5% of those technologies). Indeed, only four technologies are in the supply-side group, one at the dissemination stage of maturity (TRL = 9.5, the *tanker for ammonia transport*), one at the commercialisation-ready stage (TRL = 6.5, *methane from H₂ plus CO₂*), and two at the concept stage (TRL = 3.5, *concentrating solar fuels* and TRL = 6, *liquid fuels from H₂ plus CO₂*). Concerning the demand side group, 57.9% of the technologies (22) are commercialisation-ready or have a higher maturity level, with seven technologies in the dissemination stage of maturity. On the other hand, 36.8% of the technologies (14) are in the prototype, and 5.3% are in the concept definition stage. The lowest

TRL value (TRL = 3) relates to the *concentrating solar fuels for synthetic hydrocarbon fuels production* on the supply side and the *quad-generation* and the *steam cracker electrification* on the demand side groups. As previously referred, the supply side's upper TRL limit is for the *ammonia transport via tanker*, with a TRL = 9.5. On the demand side, the highest TRL is achieved by *carbon capture and storage via chemical absorption for ammonia production and physical separation for methanol production*, with a TRL = 9. From a more global point of view, it is possible to conclude that the demand-side technologies are more concentrated in the prototype and concept stage of maturity (81.6%).

Concerning fossil fuel energy vector, just four technologies exist, two on the demand side and two on the supply side. The demand-side technologies are the *LPG stove* with TRL = 10 in the buildings sector and the *hybrid train* with TRL = 7 in the transportation sector. The *fluid catalytic crackers through post-combustion capture* and *oxi-fuel capture* are the two supply-side technologies with TRL = 3.5 and TRL = 5, respectively.

Finally, the heat energy vector appears to have more mature technologies on the demand side (most of the technologies belong to the demand side and are related to the building sector). Indeed, more than 79% of those technologies are commercialisation-ready or have a higher maturity stage. Furthermore, more than 46% of the technologies are in the dissemination stage of maturity, and two are already proven technologies (TRL = 11): *biomass heaters using wood-burning stoves* and *hot water tanks for heat storage*. The lowest TRL of demand-side technologies is TRL = 3, concerning the *quad-generation*. Only seven technologies are considered on the supply side, with TRL ranging from 3.5 to 10. A total of four technologies (57.1%) are in the commercialisation-ready stage or have a higher level of maturity. *Solar thermal district heating* has the highest TRL value (TRL = 10, being in the dissemination level of maturity), and *thermochemical heat storage via chemical reactions* has the lowest TRL value (TRL = 3.5).

3.4. Assessment of decarbonisation strategies

3.4.1. Readiness of technology domains

The assessment of technology maturity for the identified domains in the bibliometric analysis conducted in Chapter 2 was carried out by aligning the technologies from the IEA database with the domains, considering their distinct characteristics. Some technologies were linked to multiple domains due to their diverse applications. For instance, floating hybrid

energy platforms fall under the “wind energy” and “hybrid generation system” domains. At the same time, Building Integrated Photovoltaic (BIPV) was part of both the “photovoltaic” and “microgeneration/self-consumption” domains. Additionally, it is important to stress that the 368 individual technologies were assigned to only 35 of the 41 defined domains. Indeed, none of the technologies were associated with “policy and circular measures”, “natural carbon capture and storage”, “shale natural gas”, “natural gas power generation”, “agricultural sector”, and “not specified distributed generation” domains.

The allocation of innovative technologies to different domains is the basis for assessing their readiness. In this process, the readiness scale depicted in Figure 35 is utilized. However, the various qualitative readiness levels have been consolidated into the pre-commercial ($TRL \leq 7$) and commercial ($TRL > 7$) levels of readiness for analysis convenience.

Figure 67 depicts the number of technologies linked with each domain, the percentage of technologies in “non-commercial” or “commercial” phases, and the average TRL value for the technologies accounted for within the domains. Furthermore, the figure highlights, for each technology domain, the ratio between its relevance and occurrence ranks. Those ranks were established by sorting domains in descending order based on their accumulated relevance and occurrence values. Therefore, in the occurrence rank, the first position was occupied by the domain with the highest accumulated occurrence value, the second position by the domain with the second highest occurrence value, and so on. A similar process was applied for the relevance rank case. The ratio between each domain’s relevance and occurrence ranks is then used to measure the relative attention received by each technology domain in the scientific community. In this context, emerging technologies are assumed to receive concentrated attention in a limited number of research papers. As a result, terms associated with these technologies tend to have higher relevance values, as they are more likely to appear in the keyword field and title of the documents. Conversely, technologies that have already made progress are often cited in research papers without necessarily attracting significant attention. Note that, for a specific domain of technologies, the relevance is dominant if the ratio is lower than 1, while a higher ratio emphasizes occurrence prevalence.

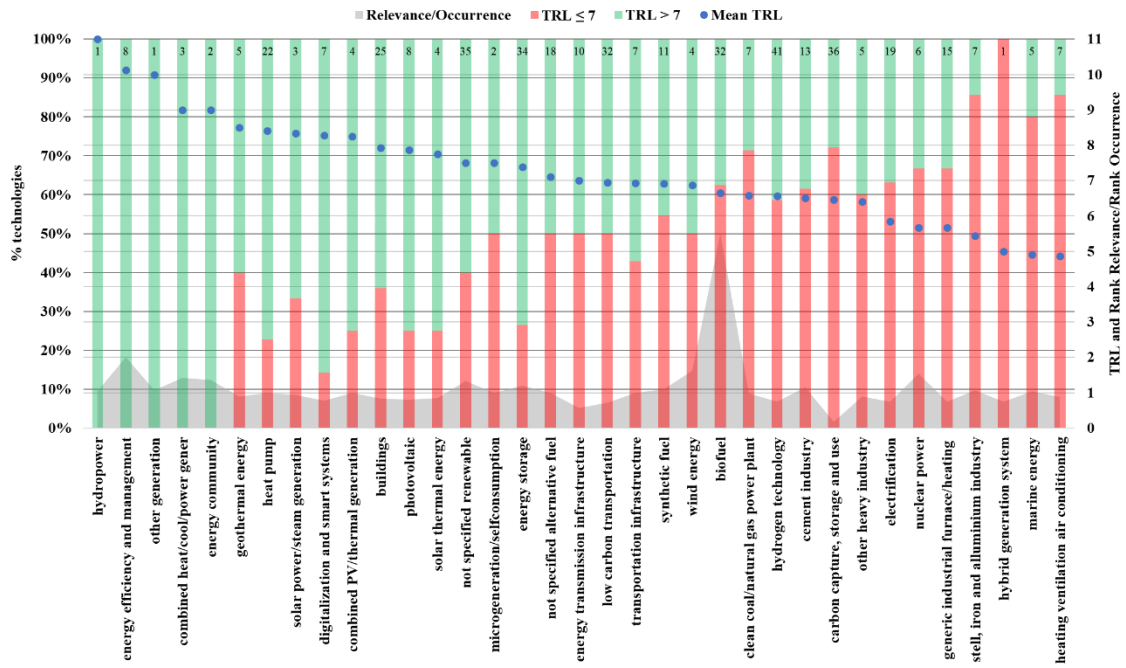


Figure 67 - Maturity of technology domains

According to the data depicted in Figure 67, certain domains notably stand out due to the number of linked technologies. Domains like “hydrogen technology”, “carbon capture, storage and use”, “not specified renewable”, “energy storage”, and “low carbon transportation” demonstrate a relatively high number of associated technologies. Conversely, domains such as “hydropower”, “other generation”, “energy community”, and “hybrid generation system” exhibit a smaller number of associated technologies.

Around 51.4% of the domains have an average TRL value of 7 or higher, meaning they are in the maturity stages at the commercial level. Additionally, four domains (11.4%) have an average TRL close to 7 (greater than 6.9). Hence, approximately two-thirds of the domains demonstrate an average Technology Readiness Level (TRL) in the commercial or near this stage.

It’s crucial to note that there are domains that encompass a higher percentage of technologies in the commercial stage. For instance, “energy storage” and “not specified renewables” have over 70% and 60% of their respective technologies in the commercial stage, respectively. Despite the high number of associated technologies, other domains present a low percentage of technologies in the commercial stage. This situation occurs, for instance, in the “hydrogen technology” domain, which has 60% of the associated technologies in a non-commercial stage.

It's worth mentioning that domains like “nuclear power” or “marine energy” present relatively low average TRL values due to a substantial percentage of technologies in the non-commercial stage.

Figure 68 offers a classification of domains based on whether their technologies predominantly cater to the supply or demand side. The infrastructure-related technologies were categorized under the supply side. The figure also indicates how domains are positioned concerning the average TRL and the quantity of integrated technologies.

According to the figure, 54% of the defined domains (19 out of the 35 in Figure 67) primarily focus on the supply side. Furthermore, an equal number of domains, consisting of nine from both the supply and demand sides, exhibit an average TRL value of 7 or higher. Therefore, roughly 56% of domains predominantly focused on supply exhibit an average TRL of 7 or greater. In contrast, only 47% of domains predominantly focused on demand demonstrate this readiness level.

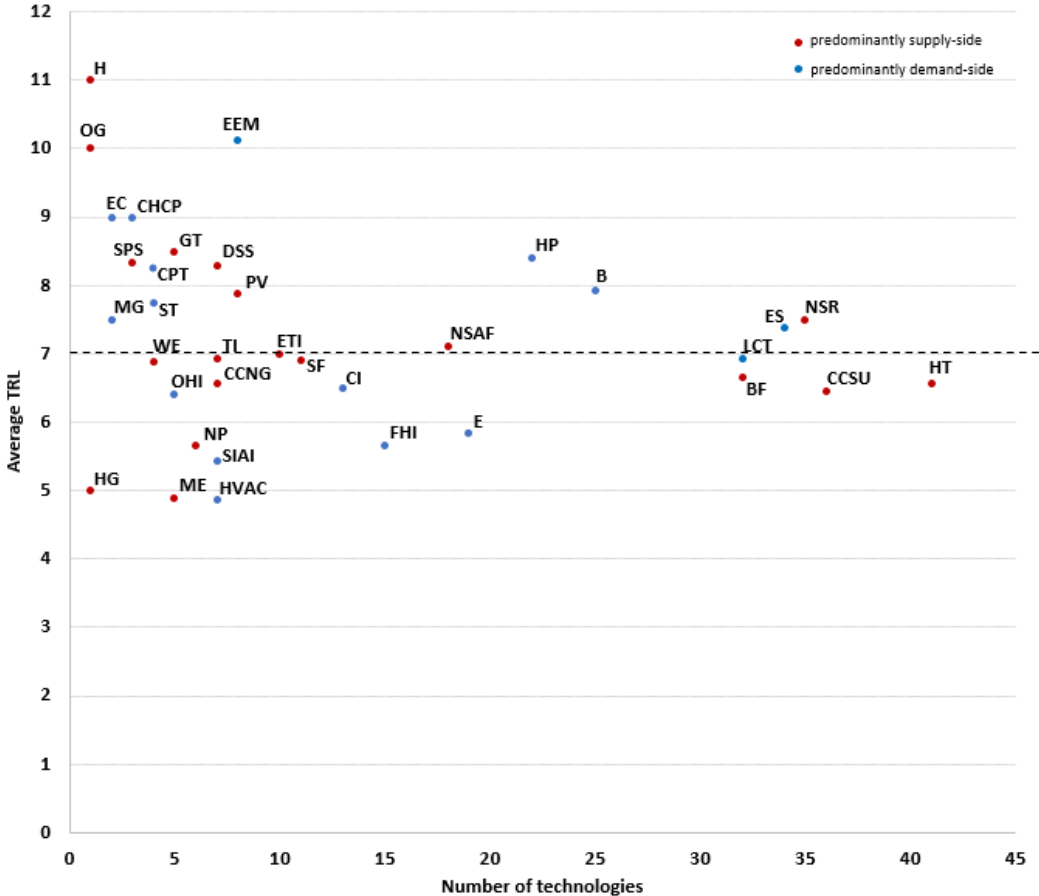


Figure 68 - Domains classification according to the prevalence of supply-side or demand-side technologies

3.4.2. Readiness, risk and potential of decarbonisation strategies

3.4.2.1. Decarbonisation strategies

In Work Package 1 (WP1) of the *Sus2Trans* project, six decarbonisation pathways were derived from a large-scale systematic literature review. Table 15 summarises the topology of the defined pathways, including a brief description of each one and a characterization considering five dimensions.

Table 15 - Typology, dimensions and description of Pathways for decarbonisation

		Pathway					
		Integrated Systems	Technology Breakthrough	Demand & Co-benefits	Decarbonization of Electricity	Electrification of Uses	Land Use & Circularity
Dimension	Energy Services	Integration of various technologies and policy measures	Advancing and deploying innovative technologies	Multi-sectoral energy demand and co-benefits (e.g. air quality)	Transition from fossil fuel-based power generation to low-carbon sources	Replacement of fossil fuel-based energy sources with electricity in end-use	Combating deforestation and soil degradation
	Economics	Macroeconomic assessments and multisectoral optimisation	Costs and benefits of deploying innovative technologies	Balancing demand reduction with co-benefits	Costs and benefits of transitioning to low-carbon power sources	Costs and benefits of electrification of end uses	Resource use efficiency and circular economy principles
	Planning	Policy measures and regulatory frameworks	Innovation planning and regulations	Behavioural change and technology adoption	Flexible and resilient electricity grid	Policies to promote electrification of end-uses	Policies to combat deforestation and soil degradation
	Infrastructure	Multisectoral energy system transformation	Deployment of innovative technologies	Infrastructure to support demand reduction	Renewable energy sources and storage technologies	Electric vehicle infrastructure and charging networks	Sustainable land management and circular economy systems
	Transition	Transitioning from a high-carbon to a low-carbon economy	Adoption of innovative technologies for deep decarbonisation	Combining technology responses with behavioural change	Transition from high-carbon power generation to low-carbon sources	Transition from high-carbon energy sources to electrification	Transition to sustainable land use and resource management
Description		This integrative approach involves macroeconomics assessments, often considered the commitments and synergies of multisectoral transformations in the energy system	This approach focuses on the development and implementation of both radical and incremental technological innovations to enable deep decarbonisations	This pathway considers the role of multisectoral energy demand and the potential co-benefits of decarbonisation	This strategy centres on decarbonising the electricity sector through an increase in the use of renewable energy sources and reducing fossil fuel-based generation	This approach involves the electrification of various end uses by replacing fossil fuel-based energy sources	This combined pathway considers the role of land use in emission reduction and prioritises resource efficiency through circular economy principles

This section explores the correlations between the above decarbonization pathways and the earlier established technology domains. The aim is to extract valuable insights into the most efficient approaches for mitigating carbon emissions and transitioning toward a low-carbon economy.

The six decarbonisation pathways were intersected with the 41 technology domains in section 2.2.4.1. This intersection was carried out in WP1 of the *Sus2Trans* project, and the outcomes are presented in Table 16. This analysis aimed to identify the five most influential domains contributing to each decarbonisation pathway.

Table 16 - Five most significant technology domains associated with decarbonisation pathways

Pathway	Most significant domains
Integrated Systems	energy efficiency and management; not specified renewables; policy and circular measures; biofuel; energy transmission infrastructure
Technology Breakthrough	biofuel; hydrogen technology; energy efficiency and management; energy storage; sythetic fuel
Demand & Co-benefits	energy efficiency and management; policy and circular measures; not specified renewables; biofuel; energy transmission infrastructure
Decarbonization of Electricity	energy storage; energy efficiency and management; hydrogen technology; wind energy; low carbon transportation
Electrification of Uses	energy efficiency and management; energy storage; not specified renewables; wind energy; heating ventilation and air conditioning (HVAC)
Land Use & Circularity	biofuel; energy efficiency and management; not specified renewables; carbon capture, storage and use; hydrogen technology

The results showed that among the 41 initially defined technology domains, only 12 emerged within the top five relevant domains for each decarbonization strategy. Furthermore, just 11 domains align with technology domains since the “policy and circular measures” domain also appeared to be associated with two decarbonisation pathways.

A noteworthy finding from the analysis is that ten of the eleven technology domains identified are among the top 20 domains with the highest accumulated relevance and occurrence values. The only exception is the “energy transmission infrastructure” domain.

3.4.2.2. Assessment of the decarbonisation strategies’ maturity

Figure 69, derived from data about the five most relevant technology domains associated with each decarbonization pathway, provides a visual summary of key elements. It allows for observing the number of technologies related to each decarbonization pathway, the average TRL of these technologies, and the percentual value of the technologies in commercial and non-commercial development stages. Therefore, this figure allows us to understand the technological landscape within decarbonization pathways, providing insights into the distribution and maturity of the related technologies.

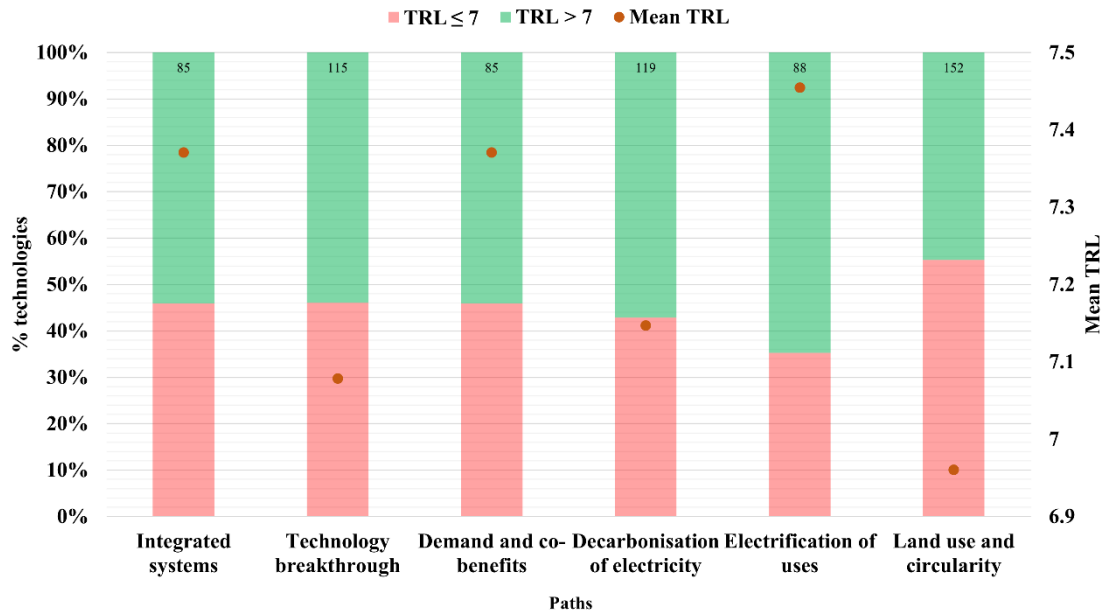


Figure 69 - Characterisation of Pathways' Readiness

The figure shows that the “Electrification of uses” pathway, despite its relatively low number of associated technologies, appears with the highest average TRL. Moreover, this pathway presents a substantial percentage of technologies in the commercial stage. Those indicators suggest a greater robustness for this decarbonization approach.

The “Technology breakthrough” and the “Decarbonization of electricity” pathways share similarities in the number of associated technologies and the percentage of technologies in the commercial stage. However, the latter holds a slightly higher average TRL value. Similarly, the “Integrated systems” and “Demand and Co-benefits” pathways exhibit the same number of associated technologies and percentages in the commercial stage (less than 50%). Moreover, their average TRL values rank second highest among the pathways.

Conversely, despite having the most considerable number of associated technologies and the highest percentage in the commercial stage, the “Land use and circularity” pathway features the lowest average TRL value.

3.4.2.3. Assessment of the risk of the decarbonisation pathways

As previously stated, the ratio between relevance and occurrence rankings offers an opportunity to assess domains' contributions to decarbonization. A higher occurrence value suggests extensive study, while elevated relevance signifies continued interest in the domain for research and solution development. Therefore, the ratio between relevance and occurrence

ranks helps gauge the potential of the technology domains to support decarbonization in the near term. Indeed, domains with lower ratio values (dominated by occurrence) indicate that those domains have already been the subject of intensive study. Conversely, higher values in the ratio (relevance dominates) suggest that the domains are still developing.

By intersecting the information regarding the ratio between relevance and occurrence ranks with the average TRL values, it becomes possible to deduce the domains' suitability in facilitating decarbonization efforts, as depicted in Figure 70. Domains in zone A are more established, with dominant occurrence and an average TRL exceeding seven (indicating commercial technologies). Therefore, those domains present a lower risk level. Conversely, domains in zone C present the highest risk level once they still have elevated research interest (indicating less development) and present non-commercial TRL. The domains in zones B and D have an intermediate level of risk.

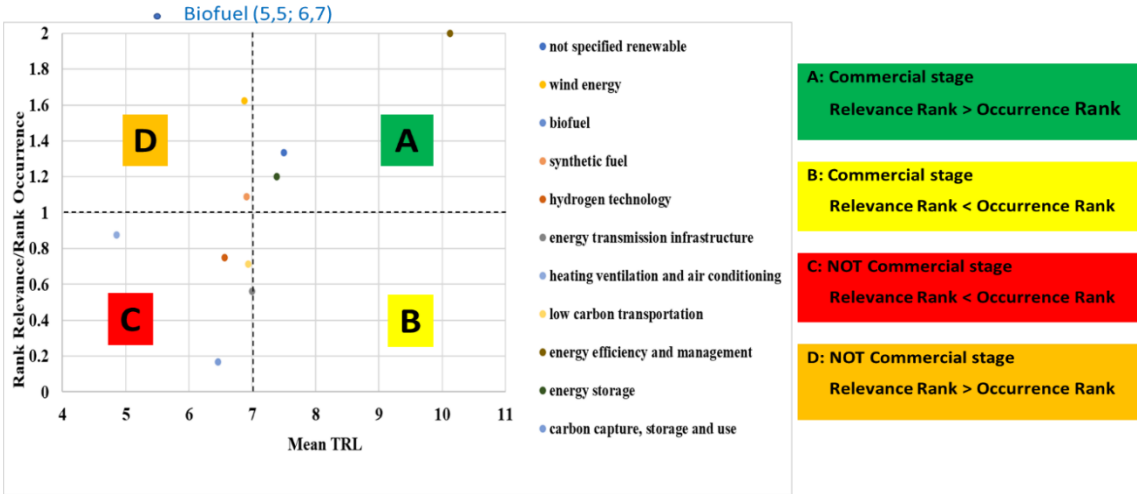


Figure 70 - Suitability of domains to support decarbonisation

Table 17 was defined based on the information in Figure 70 and shows the status of each of the five domains supporting each decarbonisation pathway (four when “policy and circular measures” integrated the set of the five domains). Based on this table, it is possible to draw some conclusions regarding the risk associated with the various proposed decarbonization pathways, highlighted in the final row of the table. A numerical scale was implemented to achieve this objective, enabling the evaluation of each domain based on its placement within zones A to D. This approach facilitates a comprehensive assessment of the risk associated with decarbonisation pathways. Domains falling within zone A were assigned a value of $Y = 1$, indicating a lower level of risk. Conversely, domains located in zone C were assigned a value of $Y = -1$, indicating a higher level of risk. Domains in zones B and D were assigned a value of

$Y = 0$, representing an intermediate level of risk. The risk level associated with each decarbonisation pathway was then calculated by summing the assigned risk values for each domain associated with the pathway and dividing it by the number of associated domains (N_i). The risk level for each pathway is represented in the last line of the Table 17, with “-“ meaning less risk and “----” representing higher risk.

Table 17 - Risk of the decarbonising pathways

Domains	Pathways (WP1)					
	integrated systems	technology breakthrough	demand & co-benefits	decarbonization of electricity	electrification of uses	land use & circularity
energy efficiency and management	A	A	A	A	A	A
not specified renewable	A		A		A	A
biofuel	D	D	D			D
energy transmission infrastructure	C		C			
hydrogen technology		C		C		C
energy storage		A		A	A	
synthetic fuel		D				
wind energy				D	D	
low carbon transportation				C		
heating, ventilation and air conditioning					C	
carbon capture and storage and use						C
Risk	--	---	--	----	-	----

Notably, following this analysis, the “Electrification of uses” approach appears less risky. In contrast, the “Decarbonisation of electricity” and “Land use and circularity” pathways pose a higher risk.

3.4.2.4. Assessment of the potential of the decarbonisation pathways

Assessing the potential of each decarbonization pathway holds crucial importance in evaluating their performance. Figure 71 shows a summary characterization of each decarbonization pathway’s potential to mitigate CO₂ emissions. This figure was constructed by examining the five most influential technology domains associated with each decarbonisation pathway and utilizing Intergovernmental Panel on Climate Change (IPCC) data [77] regarding the potential of some technologies for reducing net CO₂ emissions by 2030.

This graph indicates that the “Electrification of uses” pathway presents the highest average potential for CO₂ emissions reduction. Conversely, both the “Technology breakthrough” and “Decarbonization of electricity” pathways exhibit comparatively lower potential in this regard.

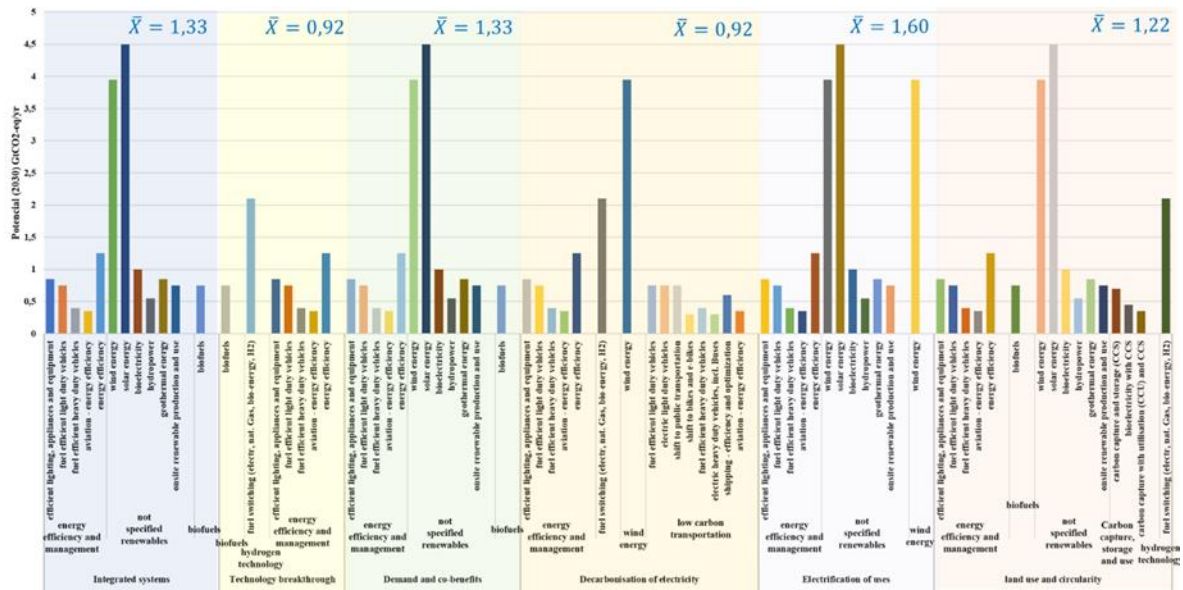


Figure 71 - Potential to reduce net CO₂ emissions of each decarbonisation pathway

3.4.2.5. Global performance

A simplified methodology was employed to conduct a comprehensive evaluation of the performance of each decarbonisation pathway. Based on the previous findings, this assessment involved ranking the pathways based on their performance in terms of their readiness and potential. The pathway with the highest average value of TRL was assigned a rank of 1 (indicating the top position in the ranking and the best performance in this factor), while the second pathway received a rank of 2, and so forth. A similar procedure was followed regarding the potential for mitigating CO₂ emissions.

In order to calculate a global score, the rank values for each pathway’s readiness and potential were combined by adding them. Subsequently, a new ranking was generated, with the pathway having the lowest sum of the rank values for readiness and potential occupying the first position, representing the best overall performance. Conversely, the pathway with the highest sum of rank values occupied the last position, indicating the worst overall performance. It is important to note that this procedure assigns equal importance to both the readiness and potential of the decarbonisation pathways.

Table 18 shows the results. Note that in the final row of Table 18, the risk associated with each decarbonisation pathway, as determined in section 3.4.2.3, is presented, where “-“ indicates the lowest risk and “----” Signifies the highest risk level.

Table 18 - Summary of results of each decarbonisation pathway

Domain	Decarbonisation pathway					
	Integrated Systems	Technology breakthrough	Demand co-benefits	Decarbonisation of electricity	Electrification of uses	Land use & circularity
Readiness (average TRL)	2	5	2	4	1	6
Potential	2	5	2	5	1	4
Sum	4	10	4	9	2	10
Rank	2	5	2	4	1	5
Risk level	--	---	--	----	-	----

The result highlights the “Electrification of uses” pathway as having both a higher readiness level and greater potential for decarbonization. Notably, this pathway also exhibits the lowest associated risk. On the contrary, the “Technology breakthrough” and “Land use & circularity” pathways appear less favourably positioned. Despite extensive research efforts, the “Technology breakthrough” pathway exhibits a higher level of risk compared to other pathways, albeit lower than the “Land use & circularity” and “Decarbonisation of electricity” pathways.

4. METHODOLOGY FOR EVALUATING AVOIDED EMISSIONS IN AN ELECTRICAL POWER SYSTEM

In the previous chapter, it was possible to conclude that the decarbonisation of economies is strongly dependent on the decarbonisation of the energy system in general and of the electrical power system in particular. Therefore, this chapter presents a model developed to assess how the decarbonisation of the electrical system may evolve over the years, considering the generation technologies that may be adopted and the expected evolution of energy demand.

4.1. Related works

Over the years, several studies have focused on quantifying avoided emissions in electrical power systems.

A study in the United States case assessed the expected avoided emissions due to the integration of PV systems [78]. The study found that the potential for avoided CO₂ emissions ranges from 670 g/W to 1500 g/W. The most significant potential for avoiding emissions emerged in areas where the electrical generation is mostly based in fossil-fuelled power plants (in particular coal-fired plants) and where the capacity factor of PV plants is higher.

In [79], various methods for calculating emissions associated with specific loads, including the charging of electric vehicles, are reviewed. The study highlights the importance of appropriately selecting methods and reaching a consensus on approaches, given the complexity of the electric sector.

A study in [80] concluded that electric vehicles can significantly reduce excess renewable energy generation in an electric system, contributing to a higher penetration of renewable sources and reduced emissions.

Alternative electricity pathways and their impact on system costs and greenhouse gas emissions are investigated in [81]. This study found that a high penetration of renewable energy with storage could save up to 6.3 million tons of carbon emissions relative to Kenya's Least Cost Power Development Plan 2017–2037.

The environmental and technical impact of adding energy storage to power systems, referred to as operating reserves, is assessed in [82]. The findings of this work indicate that adding storage could reduce emissions in systems with high renewable energy penetration. However, the effect of energy storage on emissions is highly dependent on the specific case.

An evaluation of emissions associated with energy storage in batteries across United States regions is done in [83]. Based on policy and market conditions, the results suggest that battery storage may contribute to increased or decreased emissions. Furthermore, the study concludes that it is more likely to reduce emissions in environments where wind and solar power are economically competitive than natural gas-fired generation.

An analysis of the challenges of integrating variable renewable energy in Europe, focusing on stationary storage technologies, was conducted in [84]. The study emphasises the importance of energy storage, market development, and regulations to support solar and wind energy integration in Europe.

The impact in decarbonization by 2050 due to introducing a peer-to-peer (P2P) energy market model at the municipal level in Portugal is assessed in [85]. The results evidence that both collective self-consumption communities and P2P implementation significantly reduce costs and CO₂ emissions compared to the current scenario.

4.2. Model to assess avoided emissions

As the starting point, let us assume a simplified electric power system with just one thermal-based generation technology with direct emissions (e.g., natural gas or coal-fired power plant). Moreover, as Figure 72 shows, let us consider that the generation units - conventional thermal power plant (T) and non-conventional generation (Rt) - and the system load (L) are connected to the same bus. Furthermore, the system losses are assumed to be accounted for on the load.

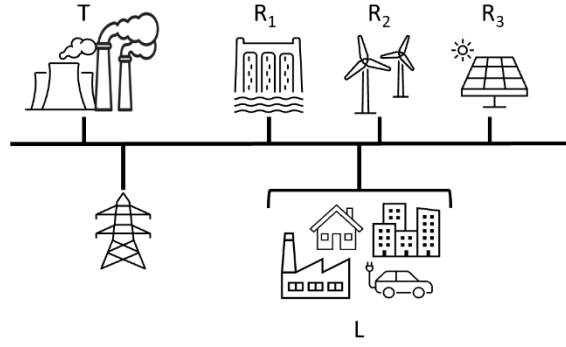


Figure 72 - Simplified power system

For a specific period Δt , the following equation applies:

$$L_{\Delta t} = T_{\Delta t} + \sum_t R_{t,\Delta t} \quad (1)$$

Where: $L_{\Delta t}$ is the system energy consumption in period Δt (MWh);

$T_{\Delta t}$ is the generated energy at period Δt through conventional generation technology with direct emissions (MWh);

$R_{t,\Delta t}$ is the energy generated at period Δt through technology t with null or lower direct emissions (such as PV, wind farms, etc.) (MWh).

The emissions of the system under such conditions and for the period Δt may be calculated by:

$$E_{\Delta t} = T_{\Delta t} \times e + \sum_t R_{t,\Delta t} \times f_t \quad (2)$$

Where: $E_{\Delta t}$ are the system emissions in period Δt (kgCO₂);

e is the specific direct emission factor of the conventional generation technology (kgCO₂/MWh);

f_t is the specific emission factor of generation technology t (kgCO₂/MWh).

In expression (2), only direct emissions from conventional technology are considered. Indeed, it is assumed that traditional power plants with emissions (thermal plants) already exist. Therefore, the indirect emissions related to installing those infrastructures have already occurred and are inevitable. Concerning the emissions of non-conventional technologies, the specific emission factors account for direct and indirect emissions, as it is intended to consider new plants to be installed over the years of the study. The direct emissions of those power plants are related to the possibility that some of these technologies may present emissions during operation, such as cogeneration units fuelled by alternative fuels or even natural gas. The indirect emissions involve establishing those power plants. Note that this model does not account for the emissions related to the operations and maintenance activities. However, those emissions may easily be included in the direct emissions.

Expression (2) may be rewritten in the form:

$$E_{\Delta t} = T_{\Delta t} \times e + \left(\sum_t R_{t,\Delta t} \right) \times f_{\Delta t} \quad (3)$$

Where $f_{\Delta t}$ is the emission factor for the mix of non-conventional generation in period Δt given by:

$$f_{\Delta t} = \sum_t f_t \times p_{t,\Delta t} \quad (4)$$

being $p_{t,\Delta t}$ the proportion of generation of technology t in period Δt , that may be obtained by:

$$p_{t,\Delta t} = \frac{R_{t,\Delta t}}{\sum_t R_{t,\Delta t}} \quad (5)$$

and:

$$\sum_t p_{t,\Delta t} = 1 \quad (6)$$

Assuming that the non-conventional generation only displaces the generation of the conventional power plants and that $L_{\Delta t} \geq \sum_t R_{t,\Delta t}$, the avoided emissions in period Δt , are:

$$AE_{\Delta t} = \sum_t R_{t,\Delta t} \times (e - f_{\Delta t}) \quad (7)$$

Where: $AE_{\Delta t}$ are the avoided emissions in period Δt (kgCO₂).

For periods where $L_{\Delta t} < \sum_t R_{t,\Delta t}$, $T_{\Delta t} = 0$, and the avoided emissions may be obtained by:

$$AE_{\Delta t} = L_{\Delta t} \times (e - f_{\Delta t}) \quad (8)$$

Note that the expression (8) assumes that unconventional generation is always dispatched before conventional generation. In practice, this occurs when there is a mechanism to guarantee the purchase of energy produced in these plants (as still happens in Portugal for some plants under a special regime) or when the sale offers made by these plants to the market have prices lower than those of conventional power plants (which is a reasonable assumption).

Expression (8) does not account for the potential avoided emissions related to the potential exported or stored energy that may result from generation surpluses. Therefore, in such circumstances, the avoided emissions in period Δt are:

$$AE_{\Delta t} = \begin{cases} \sum_t R_{t,\Delta t} \times (e - f_{\Delta t}), & \text{if } L_{\Delta t} \geq \sum_t R_{t,\Delta t} \\ L_{\Delta t} \times (e - f_{\Delta t}) & , \quad \text{if } L_{\Delta t} < \sum_t R_{t,\Delta t} \end{cases} \quad (9)$$

The annual avoided emissions may be calculated by:

$$AE = \sum_{\Delta t} AE_{\Delta t} \quad (10)$$

Where: AE are the annual avoided emissions (kgCO₂).

If the generation surpluses avoid emissions in a different power system, the expression (10) remains applicable, but expression (9) becomes:

$$AE_{\Delta t} = \begin{cases} \sum_t R_{t,\Delta t} \times (e - f_{\Delta t}) & , \quad \text{if } L_{\Delta t} \geq \sum_t R_{t,\Delta t} \\ L_{\Delta t} \times (e - f_{\Delta t}) + \left(\sum_t R_{t,\Delta t} - L_{\Delta t} \right) \times (o - f_{\Delta t}), & \text{if } L_{\Delta t} < \sum_t R_{t,\Delta t} \end{cases} \quad (11)$$

Where: o is the specific emission factor of the displaced power plants of the electrical system receiving the surplus (kgCO₂/MWh).

The previous expressions were derived assuming that just one conventional generation power plant exists in the power system. Let us now consider several thermal-based generation technologies with direct emissions, whose generation may be replaced through non-conventional generation, as shown in Figure 73.

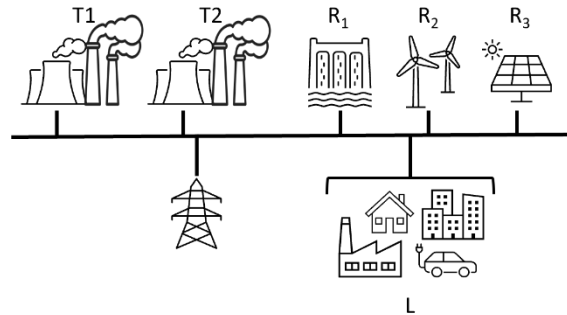


Figure 73 - Power system with several conventional power plants

It is important to stress that conventional thermal-based generation technologies may present different values of direct emissions according to the primary energy they use (coal, natural gas, etc.). Another relevant issue is that non-conventional generation will tend to replace the generation of thermal power plants with higher generation costs. The specific emission factor of the displaced thermal generation may be calculated as follows:

$$e_{\Delta t} = \sum_i (p_{i,\Delta t} \times e_i) \quad (12)$$

Where: e_i is the specific emission factor of generation technology i (kgCO₂/MWh).

$p_{i,\Delta t}$ is the share of the total thermal generation that, for the technology i and period Δt , is replaced by non-conventional plants. This parameter is calculated by:

$$p_{i,\Delta t} = \frac{T_{Ri,\Delta t}}{\sum_i T_{Ri,\Delta t}} \quad (13)$$

Where: $T_{Ri,\Delta t}$ is the generation of the conventional thermal power plant i that, in period Δt , is replaced by non-conventional generation. As expected:

$$\sum_i p_{i,\Delta t} = 1 \quad (14)$$

Note that expressions (9) to (11) remain applicable, being only necessary to replace the parameter e by $e_{\Delta t}$.

So far, the model assumes that generation and load are interconnected to the same bus. Thus, the model does not allow accounting for the impact on network losses resulting from non-conventional generators connected to different voltage levels (LV, MV, HV, etc.). However, generating electricity closer to the consumption points, as shown in Figure 74, may avoid losses in the upstream networks. As a result of the avoided losses, less electricity has to be generated, which can contribute to preventing emissions.

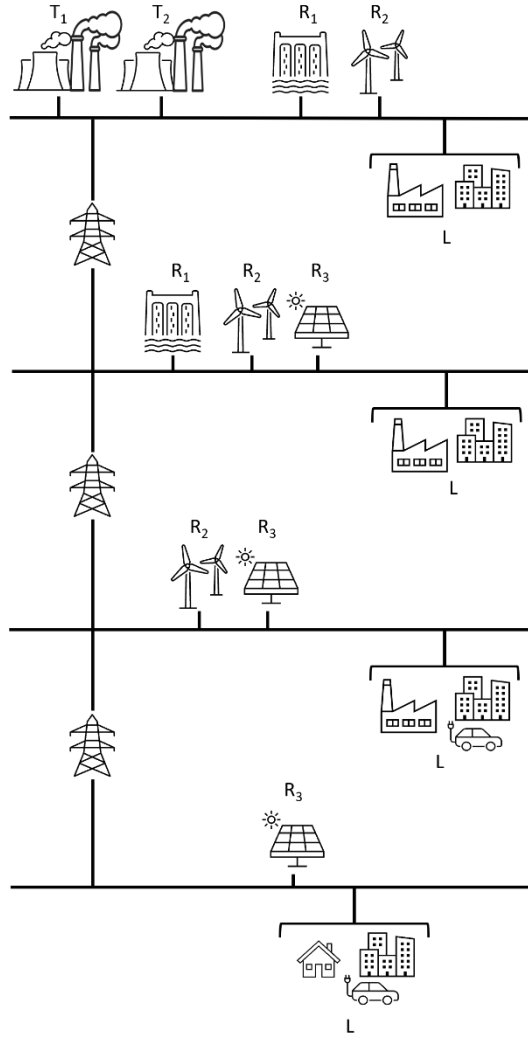


Figure 74 - Power system with non-conventional generation distributed on the system

When network losses are considered, generating 1 kWh of electricity in a non-conventional plant downstream of the conventional generation bus represents more than 1 kWh of generation in the referred bus. Thus, the total generation of a specific non-conventional technology may be modelled by:

$$R'_{t,\Delta t} = \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \quad (15)$$

Where: $R'_{t,\Delta t}$ is the total (“equivalent”) generation of non-conventional technology t , in period Δt , referred to the bus to which conventional thermal power plants are interconnected (adjusted for avoided losses) (kWh);

- 1) $R_{t,p,\Delta t}$ is the generation of non-conventional power plants of technology t connected to network p , in period Δt , referred to the bus to which the power plant is connected (kWh);
- 2) p is the set of networks to which non-conventional power plants may be connected (transmission, distribution – HV, MV, LV);
- 3) $\delta_{r,\Delta t}$ is the avoided losses factor for network r and period Δt ;
- 4) β is the set of networks that includes the network to which the generator is connected and the upstream networks. Note that $\beta \subseteq p$.

Expressions (9) and (11) may be rewritten to account for network avoided losses as:

$$AE_{\Delta t} = \begin{cases} \sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}), & \text{if } L_{\Delta t} \geq \sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \\ \sum_p L_{p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}) & , \quad \text{if } L_{\Delta t} < \sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \end{cases} \quad (16)$$

$$AE_{\Delta t} = \begin{cases} \sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}) & , \quad \text{if } L_{\Delta t} \geq \sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \\ \sum_p L_{p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}) + \left(\sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) - L_{\Delta t} \right) \times (o - f_{\Delta t}), & \text{if } L_{\Delta t} < \sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \end{cases} \quad (17)$$

The total avoided emissions remain calculated by expression (10).

4.3. Inclusion of energy storage systems

The increasing penetration of renewable energy sources may result in periods where energy generation surpasses consumption. On the other hand, the intermittency that characterizes non-conventional generation, particularly in wind and photovoltaic plants, will result in periods in which the non-conventional generation is higher than total consumption. Therefore, energy storage systems may be helpful to store the surpluses occurring in some periods for later use (when the generation of non-conventional sources is lower than consumption), with potential advantages concerning avoided emissions. Moreover, the storage systems may help in grid management, making those units essential in the future.

So far, the model does not account for integrating storage systems in the grid. It is important to stress that storage integration in the power system networks can be more centralized or distributed, as Figure 75 shows. The more distributed approach increases the “electrical proximity” between the storage systems and the consumption. In this case, the storage systems tend to present lower capacity and to be integrated into individual or collective self-consumption arrangements, energy communities, microgrids, etc. The more concentrated approach implies storage systems of high or medium capacity that companies may explore with a business related to energy storage and selling. Moreover, non-conventional power plants may also adopt storage systems to decouple energy generation and sales. This situation may be beneficial when the energy generated is sold on a market basis, making it possible to offer energy when better remuneration is expected.

Integrating storage systems into the electric networks can also contribute to avoiding network losses and emissions. Therefore, the model presented above needs to be complemented.

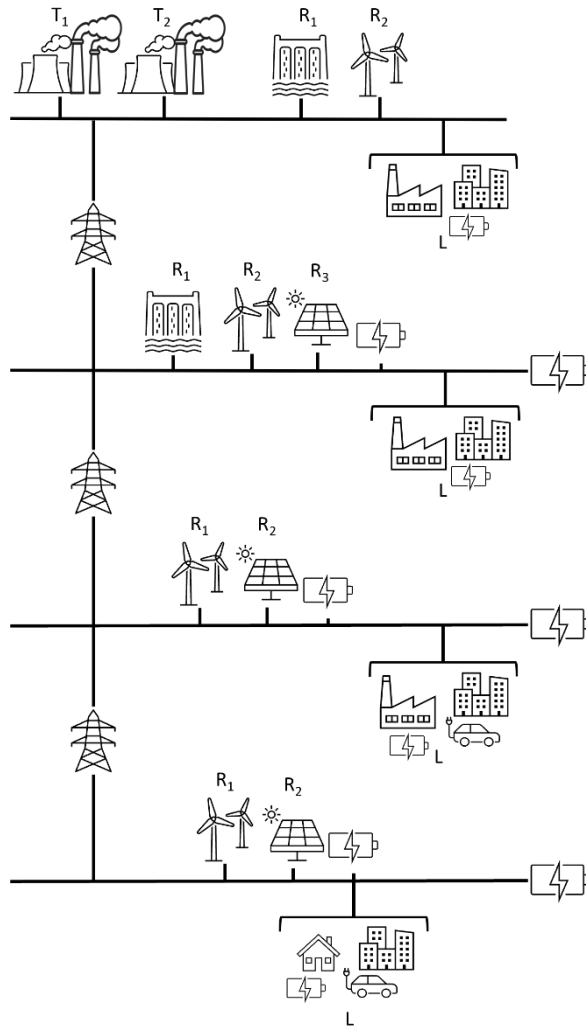


Figure 75 - Power system with storage systems

The model presented in the following assumes that:

- 1) a storage system acts like a load when charging, consuming the excess energy generated and as a supply source when discharging;
- 2) a storage system located at network p only charges if $\sum_t R_{p,t,\Delta t} > L_{p,\Delta t}$. Moreover, only energy from non-conventional generation located at network p is used to charge the storage systems located in the same network p ;
- 3) a storage system of network p discharge as soon as $\sum_t R_{p,t,\Delta t} < L_{p,\Delta t}$, supplying loads of the network to which it is connected. Furthermore, the storage systems of a network p discharge to supply loads located at downstream networks if the generation on those networks is not sufficient to cover its load;
- 4) the storage systems only discharge the energy that the non-conventional generation and the surpluses of upstream networks cannot provide. Therefore,

the excesses of non-conventional generation will only be stored if all the load of downstream networks is fulfilled;

- 5) the power only flows from the upstream to downstream networks, meaning that the storage capacity at each network is sufficient to store all energy surplus that may occur on that network;
- 6) the losses associated with energy flow to the storage systems are neglected. This assumption is based on the expectation that the storage systems will be near the generation points.

The above assumptions imply that the storage systems only store surpluses of energy generated on non-conventional sources connected to the same network to which the storage systems are connected. Furthermore, the storage systems only discharge to supply energy shortfalls in the network to which they are connected and to downstream networks.

To clarify the assumption (4), let's use the example of Figure 76. For the sake of simplicity, only three network levels are considered, and arbitrary energy generation and consumption values were assumed for just one period Δt . Moreover, in the first approach, we neglect the system losses.

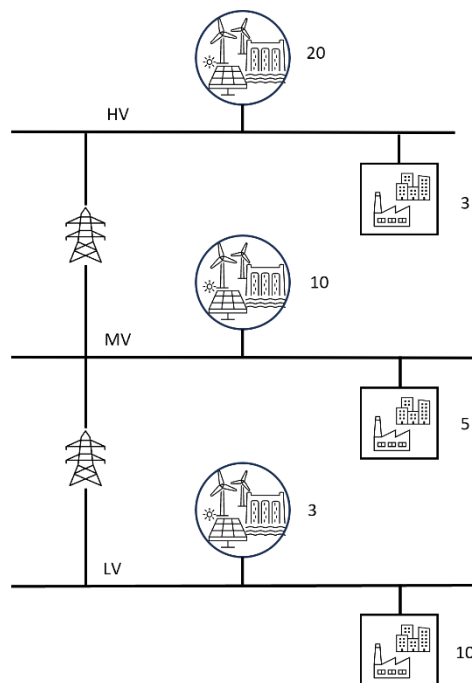


Figure 76 - Example of the mode of operation assumed for energy storage

As seen in the figure, the three units of electricity generated on the LV network are insufficient to supply the ten units consumed by the load on the same network. Therefore, the seven missing energy units must come from the upstream network to satisfy the consumption. Thus, no energy surplus exists to be stored on storage systems installed at the LV network. On the other hand, an excess of five electricity units exists in the MV network, which will supply part of the seven energy units missing in the LV network. Thus, no energy will also be stored on storage systems connected to the MV network. In turn, a surplus of 17 energy units exists in the HV network, which may be partially used to fulfil the energy consumption of load on the LV network. The remaining energy (the surplus not supplied to the downstream network) may be stored in the storage units connected to the HV network. If the electrical system were ideal (without losses), fifteen units of electricity would be sent to the storage systems.

However, in a real electric system, the electricity available to be stored on storage systems connected to the HV network will be lower than fifteen units since some energy will be lost when flowing in networks.

Considering losses means that of the three units of energy generated in the LV network, only $\frac{3}{(1+\gamma_{LV})}$ will actually be devoted to consumption. Assuming $\gamma_{LV} = 10\%$, only 2.7 energy units are delivered to the consumption, resulting in a deficit of 7.3 energy units in the LV network.

Similarly, the energy needed to meet consumption in the MV and HV networks will be higher than 5 and 3, respectively, due to the impact of network losses. Indeed, because the consumption of these networks is satisfied by local generation (on the same network), the energy needed to satisfy consumption can be calculated by $5 \times (1 + \gamma_{MV})$ and $3 \times (1 + \gamma_{HV})$, respectively. Assuming $\gamma_{HV} = 5\%$ and $\gamma_{MV} = 8\%$, the energy effectively needed to satisfy the consumption is 5.4 in the case of the MV network and 3.15 energy units in the case of the HV network. Therefore, the MV and HV networks will have surpluses of 4.6 and 16.85 energy units, respectively.

The existing surpluses in the HV and MV networks can be used to partially or fully mitigate the deficit in the LV network. According to the previously established assumptions, the MV network surplus will be the first to be considered to satisfy the LV network deficit. However, the surplus of the MV network should be at least equal to $7.3 \times (1 + \gamma_{MV}) \times (1 + \gamma_{LV}) = 7.3 \times (1 + 0.08) \times (1 + 0.1) = 8.67$ energy units to fully satisfy the LV deficit. As previously evidenced, the surplus in the MV equals 4.6 energy units, resulting in

$$\frac{4.6}{(1+\gamma_{LV}) \times (1+\gamma_{LV})} = \frac{4.6}{(1+0.08) \times (1+0.1)} = 3.87$$
 energy units that effectively will be delivered to the LV consumption. Thus, the LV network will still have a deficit of 3.43 energy units, which may be satisfied by the HV network. To fully satisfy the remaining LV network shortfall, an amount equal to $3.43 \times (1 + \gamma_{HV}) \times (1 + \gamma_{MV}) \times (1 + \gamma_{LV}) = 3.43 \times (1 + 0.05) \times (1 + 0.08) \times (1 + 0.1) = 4.28$ of the surplus in the HV network will be used to supply consumption in the LV network. Therefore, the final value of the surplus in the HV network equals $20 - 3.15 - 4.28 = 12.57$ energy units, which will be sent to the storage systems located at the HV network. Remember that no energy will be stored at the MV network once all the initial surplus is used to supply consumption in the LV network.

Note that energy storage would occur in all three system networks if the generation on each one of those networks surpasses the respective consumption. For example, if a generation of 12 units of electricity in the LV network is assumed, the energy to be stored in LV storage systems can be calculated by $12 - 10 \times (1 + \gamma_{LV}) = 12 - 10 \times (1 + 0.1) = 1$. If the conditions (generation and consumption) of the MV and HV networks remain the same as previously mentioned, the energy sent to their storage systems is, respectively, $10 - 5 \times (1 + \gamma_{MV}) = 10 - 5 \times (1 + 0.08) = 4.6$, and $20 - 3 \times (1 + \gamma_{HV}) = 20 - 3 \times (1 + 0.05) = 16.85$ energy units.

As previously stated, the network losses associated with energy flow to the storage systems are neglected in this work. However, it is essential to note that the actual stored energy in each network will be lower than the values mentioned above, as the charging process is not 100% efficient. Therefore, if the charging efficiency equals 97%, the energy effectively stored at LV, MV, and HV networks will be 0.97, 4.46, and 16.34 energy units, respectively. Moreover, the discharge efficiency will also impact the energy available to be used by discharging the storage systems, as discussed below.

The above explanation shows that calculating the energy stored in each network p for each period Δt depends on two factors: the availability of non-conventional generation surplus in network p and the potential need to use the surplus (totally or partially) to satisfy energy consumptions of networks downstream the network p .

The difference between non-conventional generation and load at each network p for each Δt period, denoted by $D_{p,\Delta t}$, is given by:

$$D_{p,\Delta t} = \sum_t R_{t,\Delta t}^p - L_{\Delta t}^p \quad (18)$$

Note that in equation (18), the network losses associated with the energy flow are accounted for in the load value (as discussed in the preceding sections (4.2)). Even so, the losses will be explicitly considered in the following equations for enhanced clarity and understanding.

Note that if $D_{p,\Delta t} > 0$ the network p has a surplus of generation and may supply consumption (totally or partially) of downstream networks. Conversely, if $D_{p,\Delta t} < 0$ the network p has a shortfall of energy, which upstream networks with generation surplus in the same period may satisfy (totally or partially). To improve the readability of the upcoming equations, we will refer to surpluses as $E_{p,\Delta t}$, and shortfalls as $N_{p,\Delta t}$. Therefore:

$$E_{p,\Delta t} = \begin{cases} D_{p,\Delta t}, & \text{if } D_{p,\Delta t} > 0 \\ 0, & \text{if } D_{p,\Delta t} \leq 0 \end{cases} \quad (19)$$

$$N_{p,\Delta t} = \begin{cases} 0, & \text{if } D_{p,\Delta t} > 0 \\ |D_{p,\Delta t}|, & \text{if } D_{p,\Delta t} \leq 0 \end{cases} \quad (20)$$

The energy in each period Δt available to be stored at each network p is calculated through the algorithm presented in Figure 77. The way to calculate the values needed to apply this flowchart is shown below.

As can be seen, a bottom-up approach is employed. Indeed, analysing energy values to be stored starts from the networks with the lowest voltage and progresses towards networks with higher voltage levels. The reason for adopting this approach is because of the assumptions mentioned earlier, which state that power solely flows from upstream networks to downstream networks.

It is important to note that the flowchart depicted in Figure 77 is applied on a per-network basis within the electrical system (specifically, the LV network corresponds to $p = 1$, the MV network to $p = 2$, and so forth, culminating with the VHV network designated as $p = 5$). Another crucial consideration is that given the assumption that energy only flows from upstream to downstream networks, the flowchart and the subsequent equations are constrained by the condition $p \geq n$.

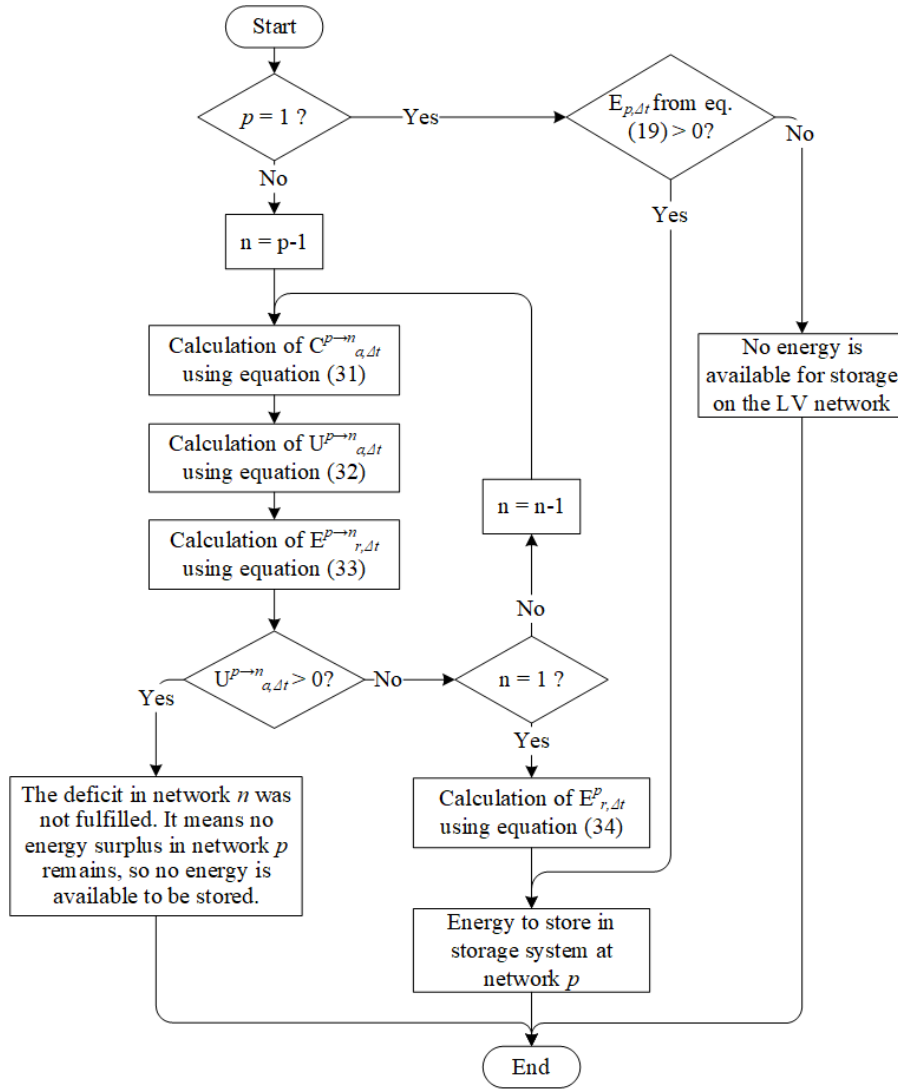


Figure 77 - Algorithm to calculate the energy to be stored in each network level

Note that the algorithm uses other variables that must be calculated derived from the information previously obtained for each network p relating to shortfall ($N_{p,\Delta t}$) or surplus ($E_{p,\Delta t}$) situations. A surplus in a network p implies the assessment of eventual shortfall situations in downstream networks. The LV network is an exception to this procedure since no downstream networks exist. Therefore, the surpluses on the LV network are immediately directed to the storage systems of this network. In the remaining networks, the surpluses will only be sent to the respective storage systems if the downstream networks do not have a shortfall situation. Moreover, it is assumed that the energy surplus of network p is first allocated to the nearest network and progressively extends to the more distant networks as long as sufficient energy is available. Hence, if there is an excess supply in network p , the immediate downstream network ($p-1$) will be checked to determine if it lacks sufficient energy ($N_{n,\Delta t} > 0$). In such a

scenario, the surplus of network p will be used to satisfy (entirely or partially) the shortfall in the network n . Therefore, the remaining surplus in network p may be calculated by:

$$E_{r,\Delta t}^{p \rightarrow (p-1)} = \begin{cases} E_{p,\Delta t} - N_{a,\Delta t}^{p-1}, & \text{if } E_{p,\Delta t} > N_{a,\Delta t}^{p-1} \\ 0, & \text{otherwise} \end{cases}, \quad (21)$$

Where: $E_{r,\Delta t}^{p \rightarrow (p-1)}$ is the remaining surplus in network p after delivering energy to the immediate downstream network ($p-1$) (MWh);

$E_{p,\Delta t}$ is the initial value of surplus in network p in the period Δt (MWh);

$N_{a,\Delta t}^{p-1}$ is the shortfall of energy in the immediate downstream network ($p-1$) adjusted for the network losses, in the period Δt (MWh), calculated by:

$$N_{a,\Delta t}^{p-1} = N_{\Delta t}^{p-1} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) \quad (22)$$

Where: θ is the set that includes networks p and $p-1$;

$\gamma_{i,\Delta t}$ is the average loss factor of network i , in period Δt (%);

If there is a remaining surplus ($E_{r,\Delta t}^{p \rightarrow (p-1)} > 0$), network p can provide energy to the following downstream network ($p-2$) in case of a shortfall. In this scenario, the remaining surplus of network p must be recalculated as follows:

$$E_{r,\Delta t}^{p \rightarrow (p-2)} = \begin{cases} E_{p,\Delta t}^{p \rightarrow (p-1)} - N_{a,\Delta t}^{p-2}, & \text{if } E_{p,\Delta t}^{p \rightarrow (p-1)} > N_{a,\Delta t}^{p-2} \\ 0, & \text{otherwise} \end{cases}, \quad (23)$$

Note that the value of $N_{a,\Delta t}^{p-2}$ is calculated by using the expression (22) but now the set θ includes the network p , ($p-1$) and ($p-2$).

The above approach will be implemented similarly if any additional networks downstream of network ($p-2$) face energy deficits, provided network p continues to have a remaining surplus. Therefore, we may generalize the situation as:

$$E_{r,\Delta t}^p = \begin{cases} E_{p,\Delta t} - \sum_{k=1}^S N_{a,\Delta t}^{p-k}, & \text{if } E_{p,\Delta t} > \sum_{k=1}^S N_{a,\Delta t}^{p-k} \\ 0, & \text{otherwise} \end{cases} \quad (24)$$

Where: $E_{r,\Delta t}^p$ represents the remaining surplus of network p after delivering energy to downstream networks experiencing a shortfall.

Note that the energy that will be sent to be stored at the network p equals $E_{r,\Delta t}^p$.

At this point, it is essential to emphasize that equation (24) applies only when all networks downstream network p do not have an energy surplus. However, as depicted in Figure 76, it may happen that specific networks downstream exhibit an energy surplus while others experience a deficit. Furthermore, it is essential to note that the surplus of network p may not be adequate to fulfil the immediate downstream network's deficit completely.

In such circumstances, the assumptions already mentioned are applied, namely the one that establishes that the nearest upstream network will initially address any shortfall in the downstream networks. For the sake of simplicity, let's consider the example shown in Figure 76. The MV network will primarily fill the LV network's deficit. If a shortfall persists, electricity from the HV network will be employed. Therefore, the energy from the HV network that will be used to cover the deficit in the LV network will only correspond to the amount not satisfied by the MV network, taking into account network losses.

Thus, when determining the energy provided by network p to any downstream network other than the immediate one ($p-1$), it is crucial to consider any energy supplies originating from the networks between network p and the deficit network ($(p-2)$, $(p-3)$, etc.). Resuming the example of Figure 76, the contribution of MV to the LV deficit ($C_{a,\Delta t}^{MV \rightarrow LV} = C_{a,\Delta t}^{2 \rightarrow 1}$) may be calculated by:

$$C_{a,\Delta t}^{MV \rightarrow LV} = C_{a,\Delta t}^{2 \rightarrow 1} = \begin{cases} N_{a,\Delta t}^1, & \text{if } E_{r,\Delta t}^2 \geq N_{a,\Delta t}^1 \\ E_{r,\Delta t}^2, & \text{if } E_{r,\Delta t}^2 < N_{a,\Delta t}^1 \end{cases} \quad (25)$$

Thus, the remaining value of the energy deficit in the LV network must be updated as follows:

$$U_{a,\Delta t}^{2 \rightarrow 1} = \begin{cases} 0 & , \quad \text{if } E_{r,\Delta t}^2 \geq N_{a,\Delta t}^1 \\ \frac{N_{a,\Delta t}^1 - E_{r,\Delta t}^2}{\prod_{i \in \theta} (1 + \gamma_{i,\Delta t})} & , \quad \text{if } E_{r,\Delta t}^2 < N_{a,\Delta t}^1 \end{cases} \quad (26)$$

Where: $U_{a,\Delta t}^{2 \rightarrow 1}$ is the remaining deficit in the LV network (1) after the MV network (2) contributes to the supply of the respective deficit.

Also, the remaining surplus in the MV network after supplying the LV network should be updated as follows:

$$E_{r,\Delta t}^{2 \rightarrow 1} = \begin{cases} E_{2,\Delta t} - C_{a,\Delta t}^{2-1} & , \quad \text{if } E_{2,\Delta t} > N_{a,\Delta t}^1 \\ 0 & , \quad \text{otherwise} \end{cases} \quad (27)$$

Since the MV network did not cover the entire deficit of the LV network, and given that the HV network has a surplus, we have:

$$C_{a,\Delta t}^{HV-LV} = C_{a,\Delta t}^{3-1} = \begin{cases} U_{a,\Delta t}^{2 \rightarrow 1} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) & , \quad \text{if } E_{r,\Delta t}^{3 \rightarrow 2} \geq U_{a,\Delta t}^{2 \rightarrow 1} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) \\ E_{r,\Delta t}^{3 \rightarrow 2} & , \quad \text{if } E_{r,\Delta t}^{3 \rightarrow 2} < U_{a,\Delta t}^{2 \rightarrow 1} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) \end{cases} \quad (28)$$

and:

$$U_{a,\Delta t}^{3 \rightarrow 1} = U_{a,\Delta t}^{2 \rightarrow 1} - \frac{C_{a,\Delta t}^{3-1}}{\prod_{i \in \theta} (1 + \gamma_{i,\Delta t})} \quad (29)$$

$$E_{r,\Delta t}^{3 \rightarrow 1} = E_{r,\Delta t}^{3 \rightarrow 2} - C_{a,\Delta t}^{3-1} \quad (30)$$

Generalizing we have:

$$C_{a,\Delta t}^{p \rightarrow n} = \begin{cases} U_{a,\Delta t}^{(p-1) \rightarrow n} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) & , \quad \text{if } E_{r,\Delta t}^p \geq U_{a,\Delta t}^{(p-1) \rightarrow n} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) \\ E_{r,\Delta t}^p & , \quad \text{if } E_{r,\Delta t}^p < U_{a,\Delta t}^{(p-1) \rightarrow n} \times \prod_{i \in \theta} (1 + \gamma_{i,\Delta t}) \end{cases} \quad (31)$$

$$U_{a,\Delta t}^{p \rightarrow n} = U_{a,\Delta t}^{(p-1) \rightarrow n} - \frac{C_{a,\Delta t}^{p \rightarrow n}}{\prod_{i \in \theta} (1 + \gamma_{i,\Delta t})} \quad (32)$$

$$E_{r,\Delta t}^{p \rightarrow n} = \begin{cases} E_{p,\Delta t} - C_{a,\Delta t}^{p \rightarrow n} & , \quad \text{if } n = (p - 1) \\ E_{\Delta t}^{p \rightarrow (n+1)} - C_{a,\Delta t}^{p \rightarrow n} & , \quad \text{otherwise} \end{cases} \quad (33)$$

Where: $C_{a,\Delta t}^{p \rightarrow n}$ is the contribution of network p to supply consumption in network n (MWh);

$R_{a,\Delta t}^{p \rightarrow n}$ is the remaining deficit of network n after partially or fully supplied by network p (MWh);

$E_{r,\Delta t}^{p \rightarrow n}$ is the remaining energy surplus in network p after supply network n (MWh);

θ is the set of networks downstream network p and upstream network n , including this one.

Therefore, equation (24) may be rewritten as:

$$E_{r,\Delta t}^p = E_{p,\Delta t} - \sum_{k \in \theta} C_{a,\Delta t}^{p \rightarrow k} \quad (34)$$

Where: $E_{r,\Delta t}^p$ represents the remaining surplus of network p after delivering energy to downstream networks experiencing a shortfall (MWh);

θ is the set of networks downstream network p and upstream network k , including this one.

Note that the result ($E_{r,\Delta t}^p$) of equation (34) is the energy available to be sent to the storage systems located in network p . However, the energy that will be stored effectively depends on the efficiency of the charging process as well as on the maximum charging power of the storage systems. Therefore, the energy stored is obtained by:

$$Ch_{p,\Delta t} = \begin{cases} E_{r,\Delta t}^p \times \eta_c & , \quad \text{if } E_{r,\Delta t}^p > 0 \wedge E_{r,\Delta t}^p \times \eta_c \leq P_{p,ch}^{max} \times \Delta t \\ P_{p,ch}^{max} \times \Delta t & , \quad \text{if } E_{r,\Delta t}^p > 0 \wedge E_{r,\Delta t}^p \times \eta_c > P_{p,ch}^{max} \times \Delta t \\ 0 & , \quad \text{otherwise} \end{cases} \quad (35)$$

Where: $Ch_{p,\Delta t}$ is the energy stored in network p , in period Δt (MWh);

η_c is the charging efficiency of the storage system, in %;

$P_{p,ch}^{max}$ is the maximum charging power of the storage systems (MW);

A crucial point to remember is that the proposed model solely considers power flows from upstream networks to downstream networks. Consequently, the model does not assume any excess energy in a particular network that remains unutilized in downstream networks or cannot be stored due to the complete storage capacity utilization. This aspect will be addressed in future studies.

The algorithm of Figure 77 allows the calculation of the energy that, in each period Δt , can be stored in the storage systems located in each network p . As explained, the surplus energy in a particular network p is first utilized to meet the demands of downstream networks, prioritizing their immediate needs over storing the excess. However, relying solely on these surpluses may not be enough to fulfil the requirements of downstream networks entirely. As mentioned earlier, energy from storage systems can be discharged in such situations to compensate for remaining shortfalls (at least partially). Thus, the discharge of storage systems occurs when it is necessary to satisfy consumption in the network to which those systems are connected and in downstream networks. It is essential to highlight that the discharge of storage systems is always intended first to satisfy the needs of the networks to which they are connected.

At this point, it is essential to note that losses that occur in networks during the flow of energy discharged from storage systems towards loads are accounted for. To clarify how storage systems' power discharge is determined, let's consider the scenario depicted in Figure 78 as an illustrative example. For the sake of simplicity, only three network levels were considered, and arbitrary values of stored energy and consumption were assumed for just one period Δt .

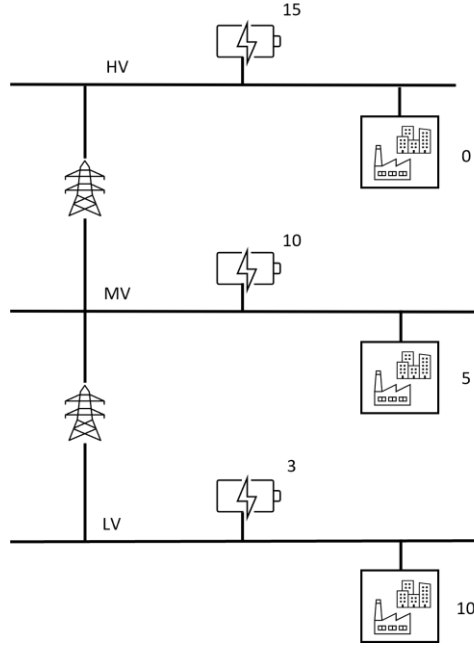


Figure 78 - Example of the operation of discharging the storage

The figure illustrates the remaining shortfalls in each network level (0, 5, and 10 energy units for the LV, MV and HV networks) that could be satisfied (totally or partially) by stored energy. It's important to note that these remaining shortfalls, denoted as $S_{r,\Delta t}^n$, represent the energy deficit in network n that persists even after the contributions of upstream networks (those with energy surpluses) have been used to meet the consumption demands of network n . Therefore:

$$S_{r,\Delta t}^n = N_{p,\Delta t} - \sum_{y \in \lambda} \frac{C_{a,\Delta t}^{y \rightarrow n}}{\prod_{i \in \lambda} (1 + \gamma_{i,\Delta t})} \quad (36)$$

Where: $S_{r,\Delta t}^n$ is the network n 's energy deficit that may be satisfied by stored energy (MWh).

λ is the set of networks downstream network y and upstream network n , including this one;

Resuming the example of Figure 78, the storage systems situated in the LV network need to discharge energy to meet the remaining shortfall within this network. However, in this case, the energy stored in the LV network (3 energy units) is insufficient to fulfil the energy shortfall.

Let us define $NS_{\Delta t}^{p \rightarrow z}$ as the energy contribution required from storage systems located in network p to meet the deficit in network z . Thus, we may write that $NS_{\Delta t}^{LV \rightarrow LV} = NS_{\Delta t}^{1 \rightarrow 1} =$

$\frac{S_{r,\Delta t}^1}{\eta_d} \times (1 + \gamma_{LV})$, being η_d the discharge efficiency of the storage systems and γ_{LV} the average losses factor for the LV network. Assuming $\eta_d = 97\%$, and $\gamma_{LV} = 10\%$, we obtain $NS_{\Delta t}^{1 \rightarrow 1} = \frac{10}{0.97} \times (1 + 0.1) = 11.34$. Hence, to completely fulfil the energy deficit of the LV network, the storage systems within that network should have a minimum of 11.34 stored energy units. However, only three energy units are stored in those storage systems (as shown in Figure 78), so the shortfall will only be partially satisfied. Moreover, only a part of that stored energy will reach the consumption due to the discharge and network losses.

Defining $NE_{\Delta t}^{p \rightarrow z}$ as the effective contribution of the storage systems placed at network p to the consumption in network z , we have $NE_{\Delta t}^{LV \rightarrow LV} = NE_{\Delta t}^{1 \rightarrow 1} = \frac{B_{\Delta t-1}^1}{(1 + \gamma_{LV})} \times \eta_d$, where $B_{\Delta t-1}^1$ is the energy stored in the LV network in the previous period ($\Delta t-1$). Thus, for the previous example, $NE_{\Delta t}^{LV \rightarrow LV} = NE_{\Delta t}^{1 \rightarrow 1} = \frac{3}{(1 + 0.1)} \times 0.97 = 2.65$ energy units. Note that the value of the energy that effectively reaches the load ($NE_{\Delta t}^{p \rightarrow z}$) also depends on the maximum discharge rate allowed by the storage system. Therefore, if the load requires more energy than the storage system can provide within a specific period, even if there is enough energy stored, the value will be limited by the maximum power discharge rate of the storage system.

In this example, all the energy stored in the LV network will be discharged. That is, the three energy units will be used. If we define $Dch_{\Delta t}^{p \rightarrow z}$ as the discharged energy from the storage systems in network p to supply consumption on network n , we have $Dch_{\Delta t}^{LV \rightarrow LV} = Dch_{\Delta t}^{1 \rightarrow 1} = \frac{NE_{\Delta t}^{1 \rightarrow 1}}{\eta_d} \times (1 + \gamma_{LV}) = \frac{2.65}{0.97} \times (1 + 0.1) = 3$. The remaining stored energy on the storage systems may be calculated by $B_{\Delta t}^{LV \rightarrow LV} = B_{\Delta t}^{1 \rightarrow 1} = B_{LV,\Delta t} - Dch_{\Delta t}^{1 \rightarrow 1} = 3 - 3 = 0$, where $B_{\Delta t}^{LV \rightarrow LV}$ is the remaining energy stored in the LV network after supplying power to the LV network.

Regarding the MV network, we may see a shortfall of energy exists, and stored energy is available. Assuming $\gamma_{MV} = 8\%$, the energy contribution required from the storage systems in the MV network is $NS_{\Delta t}^{MV \rightarrow MV} = NS_{\Delta t}^{2 \rightarrow 2} = \frac{5}{0.97} \times (1 + 0.08) = 5.57$, which is a lower value than the stored energy. Therefore, 5.57 energy units will leave the storage system in the MV network to fulfil the deficit of 5 energy units in the same network (and so, $NE_{\Delta t}^{2 \rightarrow 2} = \frac{NS_{\Delta t}^{2 \rightarrow 2}}{(1 + \gamma_{MV})} \times \eta_d = \frac{5.57}{(1 + 0.08)} \times 0.97 = 5$). Moreover, in this case, the discharged energy equals the

value of $NS_{\Delta t}^{2 \rightarrow 2}$, and may be calculated as $Dch_{\Delta t}^{2 \rightarrow 2} = \frac{NE_{\Delta t}^{2 \rightarrow 2}}{\eta_d} \times (1 + \gamma_{MV}) = \frac{5}{0.97} \times (1 + 0.08) = 5.57$. The remaining stored energy in the MV network corresponds to $B_{\Delta t}^{2 \rightarrow 2} = B_{MV, \Delta t-1} - Dch_{\Delta t}^{2 \rightarrow 2} = 10 - 5.57 = 4.43$.

All the storage systems have fully or partially supplied energy to mitigate the existing deficit in the same network they are connected to (note that no shortfall exists in the HV network). However, a deficit in the LV network still exists, which may be calculated by $S_{r, \Delta t}^{LV \rightarrow LV} = S_{r, \Delta t}^{1 \rightarrow 1} = \frac{NS_{\Delta t}^{1 \rightarrow 1}}{(1 + \gamma_{LV})} \times \eta_d - NE_{\Delta t}^{1 \rightarrow 1} = \frac{11.34}{(1 + 0.1)} \times 0.97 - 2.65 = 7.35$. This deficit may be partially satisfied by the remaining energy stored at the MV network, which equals 4.43 energy units. Indeed, to satisfy all the shortfall, the needed energy from the storage systems located at MV network would be $NS_{\Delta t}^{MV \rightarrow LV} = NS_{\Delta t}^{2 \rightarrow 1} = \frac{S_{r, \Delta t}^{1 \rightarrow 1}}{\eta_d} \times (1 + \gamma_{LV}) \times (1 + \gamma_{MV}) = \frac{7.35}{0.97} \times (1 + 0.1) \times (1 + 0.08) = 9$. Therefore, the 4.43 energy units will be used to supply LV consumption and the amount of energy that effectively reaches the LV load equals $NE_{\Delta t}^{2 \rightarrow 1} = \frac{B_{\Delta t}^{2 \rightarrow 2}}{(1 + \gamma_{LV}) \times (1 + \gamma_{MV})} \times \eta_d = \frac{4.43}{(1 + 0.1) \times (1 + 0.08)} \times 0.97 = 3.62$. Thus, the remaining deficit in the LV network becomes $S_{r, \Delta t}^{2 \rightarrow 1} = \frac{NS_{\Delta t}^{2 \rightarrow 1}}{(1 + \gamma_{LV}) \times (1 + \gamma_{MV})} \times \eta_d - NE_{\Delta t}^{2 \rightarrow 1} = \frac{9}{(1 + 0.1) \times (1 + 0.08)} \times 0.97 - 3.62 = 3.73$. The energy discharged from the storage systems of the MV network may be calculated by $Dch_{\Delta t}^{2 \rightarrow 1} = \frac{NE_{\Delta t}^{2 \rightarrow 1}}{\eta_d} \times (1 + \gamma_{LV}) \times (1 + \gamma_{MV}) = \frac{3.62}{0.97} \times (1 + 0.1) \times (1 + 0.08) = 4.43$, and thus, the remaining energy stored in the MV network is $B_{\Delta t}^{2 \rightarrow 1} = B_{\Delta t}^{2 \rightarrow 2} - Dch_{\Delta t}^{2 \rightarrow 1} = 4.43 - 4.43 = 0$, as expected.

As the LV grid still has a remaining deficit while the HV grid storage systems have available energy, it becomes necessary to calculate these systems' contribution towards meeting the LV grid's consumption needs. Assuming $\gamma_{HV} = 5\%$, the energy contribution required from the storage system in HV to compensate for the deficit in the LV may be determined by $NS_{\Delta t}^{3 \rightarrow 1} = \frac{S_{\Delta t}^{2 \rightarrow 1}}{\eta_d} \times (1 + \gamma_{LV}) \times (1 + \gamma_{MV}) \times (1 + \gamma_{HV}) = \frac{3.73}{0.97} \times (1 + 0.1) \times (1 + 0.08) \times (1 + 0.05) = 4.8$. Since there are 15 energy units in the HV network storage systems, the LV deficit will be completely suppressed. Note that from the 4.8 units of energy discharged from the HV storage systems, only 3.73 units are effectively consumed by LV load ($NE_{\Delta t}^{3 \rightarrow 1} = \frac{NS_{\Delta t}^{3 \rightarrow 1}}{(1 + \gamma_{LV}) \times (1 + \gamma_{MV}) \times (1 + \gamma_{HV})} \times \eta_d = \frac{4.8}{(1 + 0.1) \times (1 + 0.08) \times (1 + 0.05)} \times 0.97 = 3.73$). As expected, the

remaining shortfall in the LV is now equal to zero and may be calculated by $S_{r,\Delta t}^{3 \rightarrow 1} = \frac{NS_{\Delta t}^{3 \rightarrow 1}}{(1+\gamma_{LV}) \times (1+\gamma_{MV}) \times (1+\gamma_{HV})} \times \eta_d - NE_{\Delta t}^{3 \rightarrow 1} = \frac{4.8}{(1+0.1) \times (1+0.08) \times (1+0.05)} \times 0.97 - 3.73 = 0$. The amount of energy discharged from the HV storage system equals the value $NS_{\Delta t}^{3 \rightarrow 1}$, that is 4.8 energy units. This value may also be obtained by $Dch_{\Delta t}^{3 \rightarrow 1} = \frac{NE_{\Delta t}^{3 \rightarrow 1}}{\eta_d} \times (1 + \gamma_{LV}) \times (1 + \gamma_{MV}) \times (1 + \gamma_{HV}) = \frac{3.73}{0.97} \times (1 + 0.1) \times (1 + 0.08) \times (1 + 0.05) = 4.8$. Moreover, the remaining energy stored in the HV network will correspond to $B_{\Delta t}^{3 \rightarrow 1} = B_{\Delta t}^{3 \rightarrow 2} - Dch_{\Delta t}^{3 \rightarrow 1} = 15 - 4.8 = 10.2$ energy units.

The procedure outlined above, which is specific to a particular situation, can be expanded upon with the following general expressions:

$$NS_{\Delta t}^{p \rightarrow z} = \begin{cases} \frac{S_{r,\Delta t}^n}{\eta_d} \times \prod_{i \in \sigma} (1 + \gamma_{i,\Delta t}) & , \quad \text{if } p = z \\ \frac{S_{r,\Delta t}^{p \rightarrow (z-1)}}{\eta_d} \times \prod_{i \in \sigma} (1 + \gamma_{i,\Delta t}), & \text{otherwise} \end{cases} \quad (37)$$

$$NE_{\Delta t}^{p \rightarrow z} = \begin{cases} \frac{B_{p,\Delta t-1}}{\prod_{i \in \sigma} (1 + \gamma_{i,\Delta t})} \times \eta_d, & \text{if } z = p \wedge B_{\Delta t-1}^p < NS_{\Delta t}^{p \rightarrow z} \wedge \frac{B_{\Delta t-1}^p}{\prod_{x \in \sigma} (1 + \gamma_{x,\Delta t})} \times \eta_d < P_{p,dch}^{max} \times \Delta t \\ \frac{B_{\Delta t-1}^{p \rightarrow (z+1)}}{\prod_{i \in \sigma} (1 + \gamma_{i,\Delta t})} \times \eta_d, & \text{if } B_{\Delta t-1}^{p \rightarrow (z+1)} < NS_{\Delta t}^{p \rightarrow z} \wedge \frac{B_{\Delta t-1}^{p \rightarrow (z+1)}}{\prod_{x \in \sigma} (1 + \gamma_{x,\Delta t})} \times \eta_d < P_{p,dch}^{max} \times \Delta t \\ \frac{NS_{\Delta t}^{p \rightarrow z}}{\prod_{i \in \sigma} (1 + \gamma_{i,\Delta t})} \times \eta_d, & \text{if } (B_{\Delta t-1}^p \vee B_{\Delta t-1}^{p \rightarrow (z+1)}) \geq NS_{\Delta t}^{p \rightarrow z} \wedge \frac{NS_{\Delta t}^{p \rightarrow z}}{\prod_{x \in \sigma} (1 + \gamma_{x,\Delta t})} \times \eta_d < P_{p,dch}^{max} \times \Delta t \\ P_{p,dch}^{max} \times \Delta t & , \quad \text{otherwise} \end{cases} \quad (38)$$

$$Dch_{\Delta t}^{p \rightarrow z} = \frac{NE_{\Delta t}^{p \rightarrow z}}{\eta_d} \times \prod_{i \in \sigma} (1 + \gamma_{i,\Delta t}) \quad (39)$$

$$B_{\Delta t}^{p \rightarrow z} = \begin{cases} B_{p,\Delta t-1} - Dch_{\Delta t}^{p \rightarrow z} & , \quad \text{if } p = z \\ B_{\Delta t}^{p \rightarrow (z+1)} - Dch_{\Delta t}^{p \rightarrow z} & , \quad \text{otherwise} \end{cases} \quad (40)$$

$$S_{r,\Delta t}^{p \rightarrow z} = \frac{NS_{\Delta t}^{p \rightarrow z}}{\prod_{i \in \sigma} (1 + \gamma_{i,\Delta t})} \times \eta_d - NE_{\Delta t}^{p \rightarrow z} \quad (41)$$

Where: $NS_{\Delta t}^{p \rightarrow z}$ is the energy contribution needed from storage systems located in network p to fulfil the deficit in network z (MWh);

$NE_{\Delta t}^{p \rightarrow z}$ is the energy that effectively reaches network z coming from storage systems placed in network p (MWh);

η_d is discharging efficiency in %;

σ is the set of network downstream network p and upstream network z , including this one.

$Dch_{\Delta t}^{p \rightarrow z}$ is the discharged energy from the storage systems in network p to network z (MWh);

$B_{\Delta t}^{p \rightarrow z}$ is the remaining energy stored in network p after delivering energy to network z (MWh);

$B_{p, \Delta t - 1}$ is the energy stored in network p in the period $(\Delta t - 1)$ (MWh);

$S_{r, \Delta t}^{p \rightarrow z}$ represents the remaining deficit of network z after receiving energy from storage systems in network p (MWh);

At this point, it is possible to calculate the total amount of energy that has been discharged from the storage systems located at each network level in period Δt :

$$Dch_{p, \Delta t} = \sum_{z \in \sigma} Dch_{\Delta t}^{p \rightarrow z} \quad (42)$$

Where: $Dch_{p, \Delta t}$ is the discharged energy from network p (MWh);

The flowchart of Figure 79 summarizes the algorithm to calculate the abovementioned parameters. Note that, similarly to the flowchart of Figure 78, the procedure is to be applied individually to each network p , and the equations are constrained to the condition $p \geq z$.

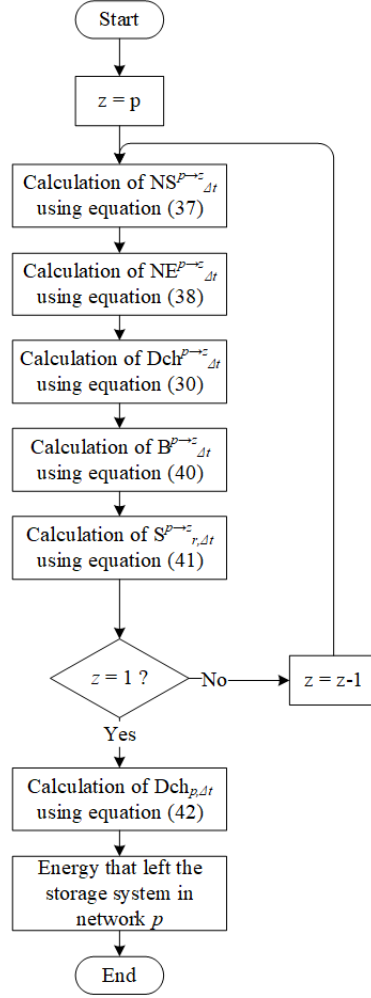


Figure 79 - Algorithm for computing the energy required from storage systems to satisfy consumption at each network p

The calculations presented in this section are limited to a specific period Δt and serve to understand the energy exchange between the networks and the storage systems. This understanding is essential for evaluating the role of storage systems in meeting the electricity consumption of each network and, in turn, determining the necessary energy generation from conventional sources like fossil-based power plants.

After acquiring knowledge on the energy used for charging and discharging the storage systems at each network level, we can calculate the energy stored in each network p in each period Δt by:

$$B_{p,\Delta t} = \begin{cases} B_{p,\Delta t-1} + Ch_{p,\Delta t} , & \text{if } Ch_{p,\Delta t} > 0 \wedge B_{p,\Delta t-1} + Ch_{p,\Delta t} \leq Cap_p^{max} \\ Cap_p^{max} , & \text{if } Ch_{p,\Delta t} > 0 \wedge B_{p,\Delta t-1} + Ch_{p,\Delta t} > Cap_p^{max} \\ B_{p,\Delta t-1} - Dch_{p,\Delta t} , & \text{if } Dch_{p,\Delta t} > 0 \wedge B_{p,\Delta t-1} - Dch_{p,\Delta t} > Cap_p^{max} \times (1 - DoD) \\ 0 , & \text{if } Dch_{p,\Delta t} > 0 \wedge B_{p,\Delta t-1} - Dch_{p,\Delta t} \leq Cap_p^{max} \times (1 - DoD) \end{cases} \quad (43)$$

Where: $B_{p,\Delta t}$ is the energy present on the storage system at network p in the period Δt (MWh);

Cap_p^{max} is the storage system's maximum capacity (MWh);

DoD is the depth of discharge in %.

It is crucial to highlight that the Depth of Discharge (DoD) in a storage system refers to the amount of a battery's capacity that has been discharged relative to its total capacity. It is commonly expressed as a percentage. For example, a battery with an 80% DoD has discharged 80% of its full capacity. The DoD is critical because it impacts the battery's overall performance, efficiency, and especially the lifespan of the storage systems. Indeed, using a higher DoD regularly can lead to faster degradation and reduced battery lifespan. Therefore, a maximum value is usually defined for the allowed DoD of the storage systems. Thus, assuming that a $DoD = 80\%$ is specified, this means that an amount of energy corresponding to 20% of the total capacity of the storage is always conserved in the system.

Please note that this model does not necessarily imply that the storage systems must be battery-based. For instance, surplus energy could power electrolyzers for hydrogen production. This stored energy in the form of hydrogen could then be used to generate energy through a fuel cell when needed. When implementing a system like this, some aspects must be accounted for. For instance, the charging efficiency should account for various factors like the efficiency of the electrolyser, the efficiency of any compression or liquefying processes involved, and the efficiency of the storage tank. On the other hand, discharging efficiency should consider the efficiency of the fuel cell. Additionally, determining the maximum power capabilities would be linked to factors such as the maximum capacity of the electrolyser, representing the maximum charging power, and the power output of the fuel cell, representing the maximum discharging power. It is essential to emphasize that accurate estimations of these values would require prior research and assessment.

With the storage system functioning as outlined, to quantify avoided emissions when storage is taken into account, expressions (16) and (17) can be reformulated as follows:

$$AE_{\Delta t} = \begin{cases} \sum_t \sum_p (R_{t,p,\Delta t} + S_{p,\Delta t}) \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}), & \text{if } L_{\Delta t} \geq \sum_t \sum_p (R_{t,p,\Delta t} + S_{p,\Delta t}) \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \\ \sum_p L_{p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}) & , \quad \text{if } L_{\Delta t} < \sum_t \sum_p (R_{t,p,\Delta t} + S_{p,\Delta t}) \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \end{cases} \quad (44)$$

$$AE_{\Delta t} = \begin{cases} \sum_t \sum_p (R_{t,p,\Delta t} + S_{p,\Delta t}) \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}) & , \quad \text{if } L_{\Delta t} \geq \sum_t \sum_p (R_{t,p,\Delta t} + S_{p,\Delta t}) \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \\ \sum_p L_{p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \times (e_{\Delta t} - f_{\Delta t}) + \left(\sum_t \sum_p R_{t,p,\Delta t} \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) - L_{\Delta t} - S_{c_{p,\Delta t}} \right) \times (o - f_{\Delta t}), & \text{if } L_{\Delta t} < \sum_t \sum_p (R_{t,p,\Delta t} + S_{p,\Delta t}) \times \left(\prod_{r \in \beta} (1 + \delta_{r,\Delta t}) \right) \end{cases} \quad (45)$$

Where $S_{p,\Delta t}$ is the energy delivered by the storage system located at network p that was stored at level p , in period Δt , that may be calculated

as:

$$S_{p,\Delta t} = \begin{cases} B_{p,\Delta t-1} - B_{p,\Delta t}, & B_{p,\Delta t} < B_{p,\Delta t-1} \\ 0, & B_{p,\Delta t} \geq B_{p,\Delta t-1} \end{cases} \quad (46)$$

The total avoided emissions remain calculated by expression (10).

5. CASE STUDY

This chapter applies the methodology introduced in Chapter 4 using the Portuguese power system as a case study.

5.1. Characterization of the Portuguese power system

5.1.1. Electricity consumption

Figure 80 displays the evolution of electricity demand in Portugal from 1990 to 2021. The data show a significant surge in electricity usage from 1990 to 2007, where consumption witnessed a remarkable increase of 105%. Due to Portugal’s economic and financial crisis, consumption decreased by 7.4% in 2010-2014. Then, a new load growth period occurred until 2017, with consumption stabilizing after that year and until 2018. As a result of the COVID-19 pandemic, consumption decreased again in 2020 and then resumed its growth, with an increase of 3.3% in 2020-2022.

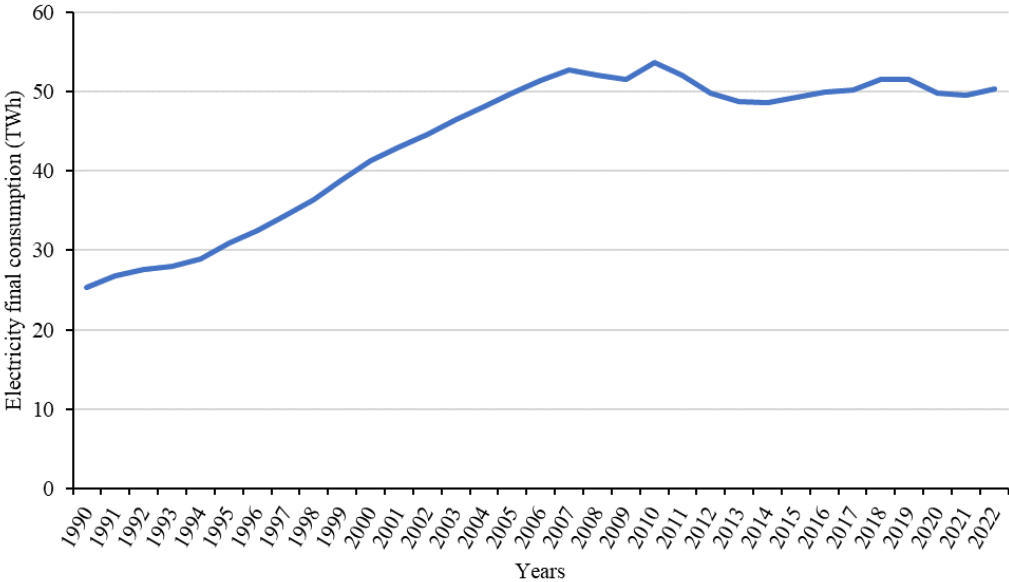


Figure 80 - Historical electricity consumption in Portugal (source: [86])

5.1.2. Electricity generation

In 2022, the total installed power in the Portuguese electrical power generation system amounted to 20.7 TW, with fossil-based plants contributing 4.5 TW [87]. Based on data provided by REN – National Electric Grids [88], Figure 81 illustrates the progression of installed capacity in Portugal, highlighting the remarkable expansion of renewable energy technologies. The deactivation of Pego and Sines coal plants (2020 onwards) has led to a significant decrease in the installed capacity of fossil-based power plants, making it crucial to emphasize this decline [89].

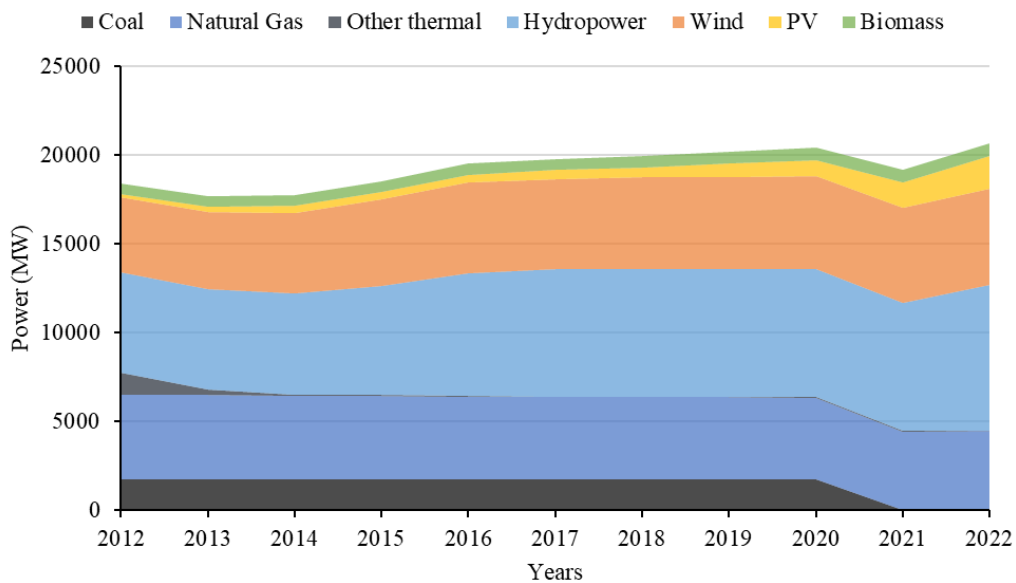


Figure 81 - Installed capacity in the Portuguese electric power generation system (2012-2022)

Table 19 presents the changes in installed capacity for the technologies depicted in Figure 81 over the past ten years, assuming that the installed capacity in 2012 serves as a reference point. Based on this information, it is possible to realize that PV technology experienced the most significant relative growth. In aggregate, it is possible to see that the installed capacity in plants based on fossil energy was reduced by 42%, mainly due to the complete phase-out of coal-based power plants. Conversely, the aggregated installed capacity in renewable sources increased by 52%. As a result of this development, renewable energy sources now account for 78% of the total installed capacity in the Portuguese electric power system. Notably, in 2012, this percentage stood at 62%.

Table 19 - Variation in installed power generation capacity (2012-2022)

	Δ (%) in 2022 compared to 2012
Hydropower	45%
Wind	28%
PV	765%
Biomass	18%
Natural Gas	-5%
Coal	-100%
Other thermal	-98%

Figure 82 shows energy generation using the different technologies installed on the Portuguese electrical system for 2012-2022.

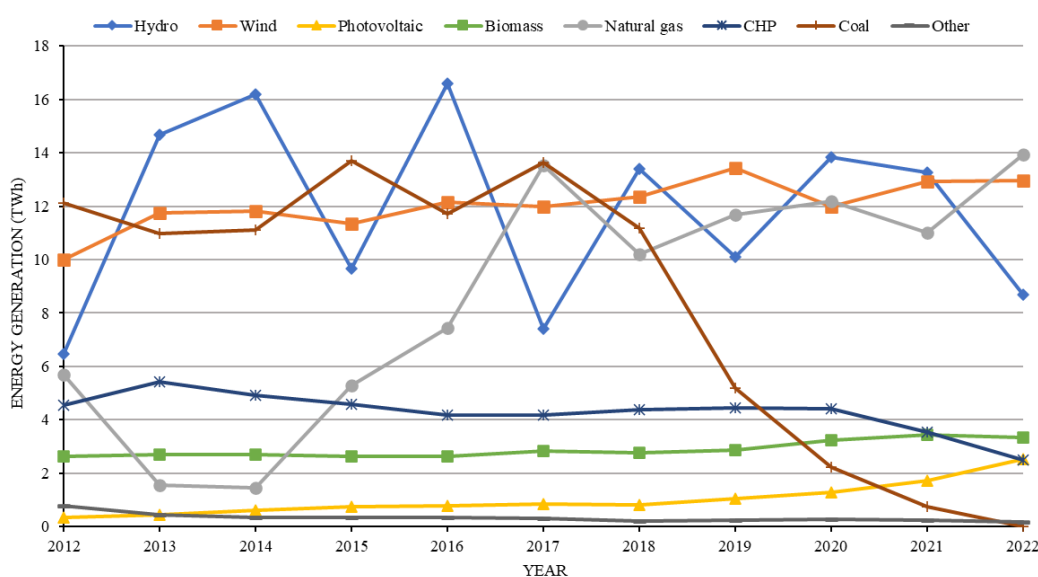


Figure 82 - Electricity generation by technology in Portugal (2012-2022)

Some relevant conclusions may be extracted from Figure 82:

1. Hydropower, wind power, and fossil-based generation have been the leading technologies over the last decade. In the case of fossil-based generation, the generation based on coal surpassed the natural gas-based generation in the first years. Moreover, in the 2012-2018 period, coal-based generation was more stable than natural-gas-based generation. Indeed, during this period, natural gas-based generation assumed the role of compensating for the variation in hydroelectric generation due to climacteric variations;
2. Coal-based production began a rapid decline in 2017, reaching zero in 2022. Therefore, natural gas-based generation experienced an increase and became

more stable over the years. However, it remains the primary mechanism for compensating deviations from hydroelectric generation (and other renewable sources);

3. There is a steady increase in wind and solar generation, with a higher relative increase in the solar case;
4. There has been a slight decline in Combined Heat and Power generation (CHP) and a slight increase in biomass-based generation in the last few years.

Thus, based on the above inferences, it is clear that the direct emissions associated with electricity generation are due to the use of fossil fuels, namely coal and natural gas. Moreover, from 2022, these emissions will only be due to using natural gas-fired power plants for electricity generation.

The installed capacity of renewable-based generation and their productivity indexes³ significantly affect the total emissions. Figure 83 shows the relationship between thermal-based power generation (coal and natural gas) and productivity indexes of renewable sources. The productivity indexes were obtained from the official data of REN [90]. The figure shows that energy generation through non-renewable sources depends on the productivity indexes of renewable-based sources, particularly hydroelectricity in the Portuguese case.

Table 20 summarises electricity generation and consumption from 2012 to 2022 and the correlation between thermal-based generation (coal, natural gas, and other thermal sources) and renewable sources (hydro, wind, and solar). Note that in column *Imp-Exp* a negative value means exportation of electricity. Moreover, the total generation is slightly higher than consumption due to the system losses. It can be concluded from the table that a significant negative correlation exists (-0.5) between thermal-based and renewable generation, meaning that the increase in renewable generation results in a decrease in thermal-based generation. Furthermore, the correlation for the last six years is more substantial, with a value of -0.75.

Moreover, the Portuguese power system is integrated into the Iberian Electricity Market (MIBEL), where renewable generation tends to be at the base of the aggregated supply curve, and the natural gas plants tend to be the marginal units. Thus, as expected, renewable generation tends to replace thermal-based generation (natural-gas-based generation in the case of the

³ Productivity index, according to [161], is an indicator that makes it possible to quantify the deviation of the total value of energy produced in a given period in relation to that which would occur if an average (hydrological, wind or solar) regime occurred.

Portuguese power system). So, it is a reasonable assumption that, in the future, the increase in renewable energy generation will decrease the power provided by natural gas power plants.

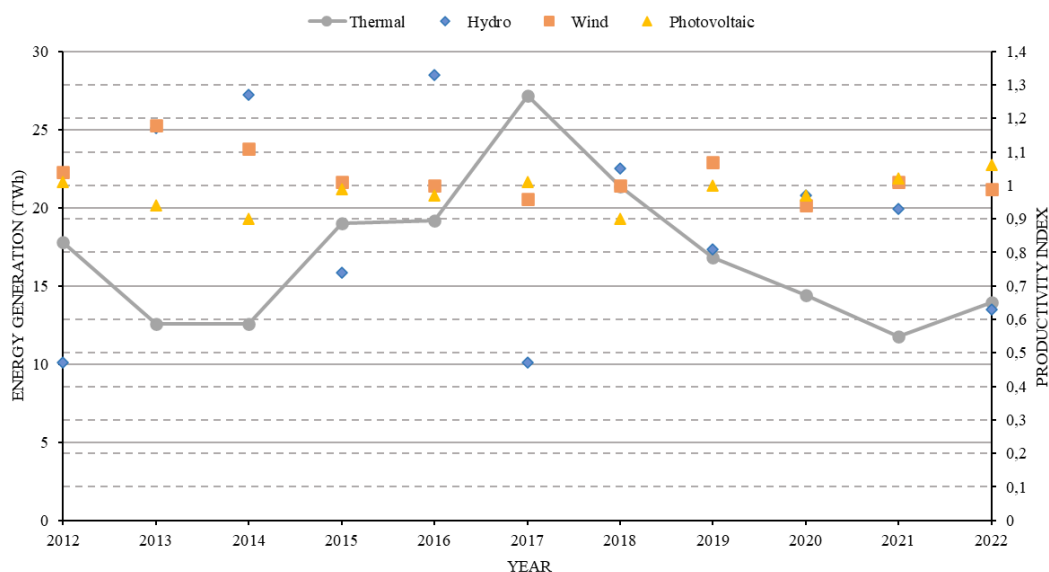


Figure 83 - Influence of productivity indexes of renewable generation on thermal-based generation

Table 20 - Energy generation and consumption in Portuguese electric system (2012-2022)

Energy summary from 2012 to 2022 in TWh								
Year	Thermal (coal+natural gas+other)	Hydro	Wind	Solar	Renewables (hydro+wind+solar)	Biomass+CHP	Imp-Exp	Cons+ Pump
2012	18,57	6,47	10,01	0,36	16,83	7,17	7,86	50,30
2013	12,98	14,67	11,75	0,44	26,87	8,11	2,78	50,37
2014	12,90	16,20	11,81	0,60	28,61	7,61	0,90	49,99
2015	19,35	9,66	11,33	0,76	21,75	7,18	2,27	50,38
2016	19,52	16,59	12,15	0,78	29,52	6,83	-5,08	50,43
2017	27,46	7,39	11,97	0,85	20,22	6,98	-2,68	51,13
2018	21,57	13,41	12,35	0,83	26,59	7,13	-2,66	50,49
2019	17,07	10,10	13,42	1,06	24,58	7,32	3,40	50,74
2020	14,68	13,83	11,98	1,27	27,08	7,63	1,45	50,89
2021	11,99	13,26	12,92	1,72	27,89	6,95	4,75	50,90
2022	14,13	8,68	12,96	2,53	24,18	5,81	9,25	53,29

Correlation between Thermal and Renewables:	-0,50
Correlation between Thermal and Renewables for the last six years (2017 to 2022):	-0,75

5.2. Scenarios for energy generation and consumption

Like most countries, especially the most developed ones, the Portuguese economy is highly dependent on energy. Therefore, energy consumption is expected to continue to increase in Portugal, even if the energy is used more efficiently. On the other hand, the challenges of

decarbonization will lead to increased electrification of developed countries' economies, including the mobility sector, reinforcing the expected increase in electricity consumption. Indeed, electrification may, on the one hand, increase energy use efficiency; on the other, it makes it possible to reduce the use of fossil energy through an increase in renewable generation. Therefore, renewable energy sources such as bio-fuel, solar power, hydropower, wind power, and wave power should be aggressively explored to ensure sufficient energy supply to support the Portuguese economy's growth in an environment-friendly manner [91].

Yet, the widespread use of renewable energies within the electrical system contributes to the emergence of technical and even economic problems related to their intermittency. Therefore, electricity storage has been seen as a critical pillar for the decarbonisation strategy once it may support the technical integration of renewable sources and provide system flexibility. According to [92], Portugal intends to have at least 100 MWh of battery storage capacity by 2030.

The assessment of the future behaviour of emissions associated with the Portuguese electrical system implies the need to define future electricity generation and consumption scenarios. Therefore, in this work, two scenarios (conservative and ambitious) for each of the evolution of installed generation capacity and electricity consumption were defined based on inputs from multiple entities and documents, including IEA, Directorate General for Energy and Geology (DGEG), Roadmap to Carbon Neutrality (RNC), and National Energy and Climate Plans (PNEC) [92] – [96].

5.2.1. Installed generation capacity scenarios

Although hydroelectric power plants currently have the highest installed capacity (approximately 8 GW) in the Portuguese electric system, none of those already mentioned entities/documents (IEA, DGEG, RNC, and PNEC) predict any increase in its installed capacity. This situation is because almost all viable hydropower resources have already been tapped into. Moreover, the previously mentioned entities and documents also do not predict an increase in installed capacity in conventional thermal plants, regardless of the technology or fuel (nuclear plants or natural gas/coal power plants with carbon capture).

Hence, the supply side of the electric power system only envisions the integration of new renewable energy sources, with a particular emphasis on wind and PV technologies, as depicted in Figure 84 and Figure 85. Moreover, it is expected that PV technology will

experience a more pronounced relative increase in the upcoming years. It is worth noting that two distinct scenarios are outlined: the ambition and the conservative.

In the ambition scenario, a more aggressive expansion of installed power is assumed in the first years, particularly concerning PV technology, which is projected to increase from around 2 GW in 2020 to 12.4 GW by 2040. The installed capacity of wind power is also expected to grow in the same scenario, but in this case, from 5.8 GW to nearly 11.7 GW.

The conservative scenario foresees an increase in the installed power of PV from 2 GW in 2020 to 12.1 GW in 2040. Furthermore, Figure 84 and Figure 85 provide evidence showing that the growth rate of PV installed capacity is lower than anticipated in the ambition scenario, particularly up until 2030. The same conservative scenario envisions that the installed capacity of wind power increases from 5.8 GW in 2020 to 11.2 GW in 2050.

Concerning biomass and CHP, both scenarios anticipate a modest increase in biomass and a decline in CHP. Regarding natural-gas-based generation, both scenarios predict the decommissioning of several power plants starting in 2025, with the largest one expected to be decommissioned by the end of 2029. The main difference between the scenarios is the rate at which the installed power will decrease from 2030 onwards, although the differences are minor.

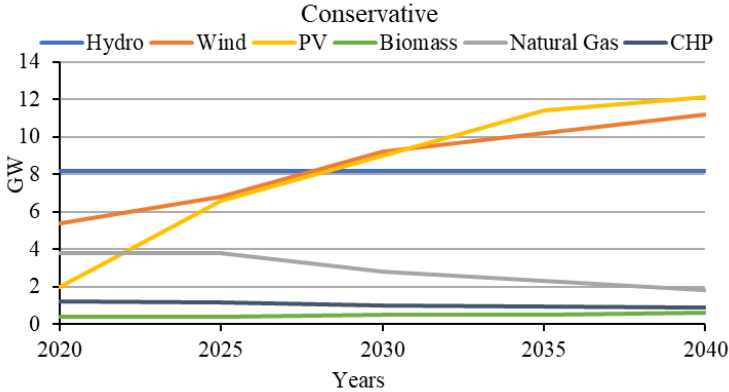


Figure 84 - Forecasted installed power on generation system – conservative scenario

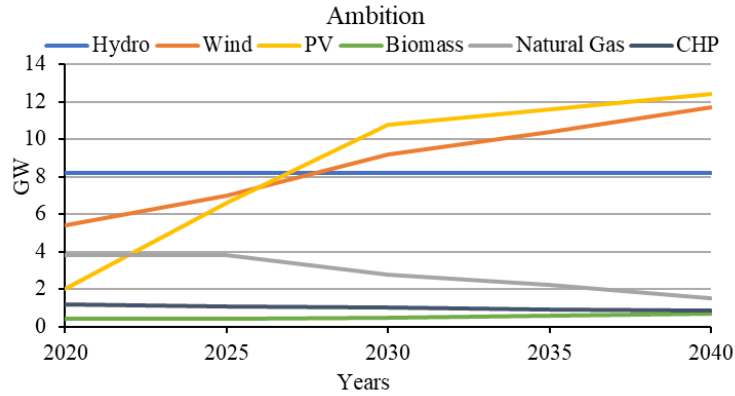


Figure 85 - Forecasted installed power on generation system – ambition scenario

It is crucial to emphasize that this section solely discusses scenarios regarding the progression of installed power within various electricity generation technologies. Projections regarding energy generation, encompassing generation profiles throughout the year, will be addressed in section 5.2.4.

5.2.2. Electricity consumption scenarios

As previously referred, there is a tendency for the electrification of economies, particularly in the energy-intensive sectors, including the mobility sector. As expected, this tendency will significantly impact the final electricity consumption.

In addition to this important factor, other factors greatly influence the evolution of electricity demand. For instance, economic factors (economic growth, development of new economic sectors (data centres), new energy-related sectors (electrolysers)) and the implementation of energy-related policies significantly affect how the consumption of energy in general and electricity in particular evolves. In the current context, energy efficiency stands out as crucial, particularly in the building sector, where substantial improvements in energy efficiency are anticipated. Furthermore, the emphasis on energy efficiency in this sector is further supported by European directives aimed at its enhancement.

Moreover, electric mobility is set to have a transformative effect on electricity consumption. The transportation sector, which accounts for a substantial portion of final energy consumption and plays a significant role in greenhouse gas emissions [97], is expected to experience substantial changes. According to the IEA Global EV Outlook report, electric vehicles (EVs) should represent 30% of sales of new terrestrial transportation in 2030 [98].

Figure 86 illustrates the anticipated growth in electricity consumption for the Portuguese electric power system. Those forecasts rely on data from the above sources (IEA, DGEG, RNC, and PNEC) and consider key factors such as economic growth, technological advancements, electric mobility, data centres, and electrolysers development.

As for installed generation capacity, two scenarios are defined: conservative and ambition. Under the conservative scenario, the consumption is expected to rise from approximately 50 TWh to 60 TWh by 2050, while in the ambition scenario, a consumption of 75 TWh is forecasted for 2050.

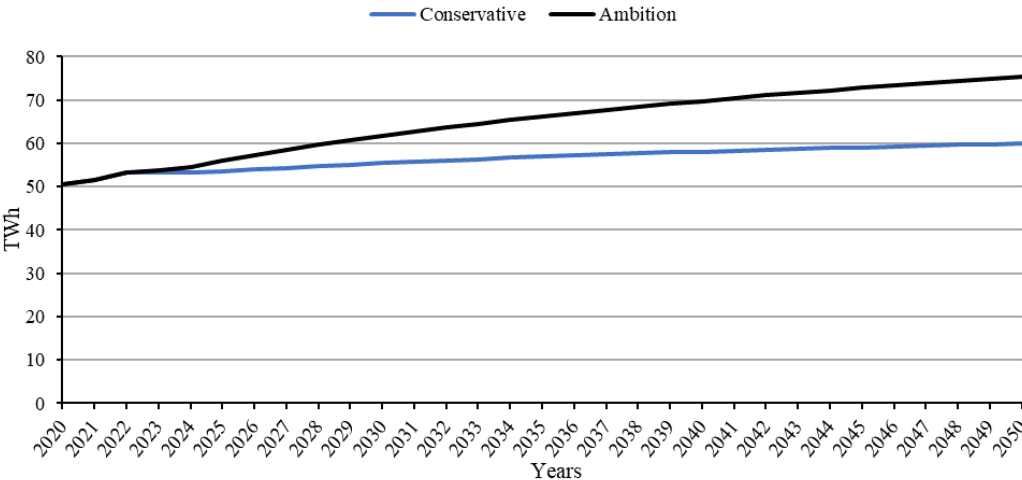


Figure 86 - Forecasts for electricity consumption – conservative and ambition scenarios

5.2.3. Global scenarios

The scenarios defined for generation installed capacity and electricity consumption may be combined to define four global scenarios, as shown in Figure 87.

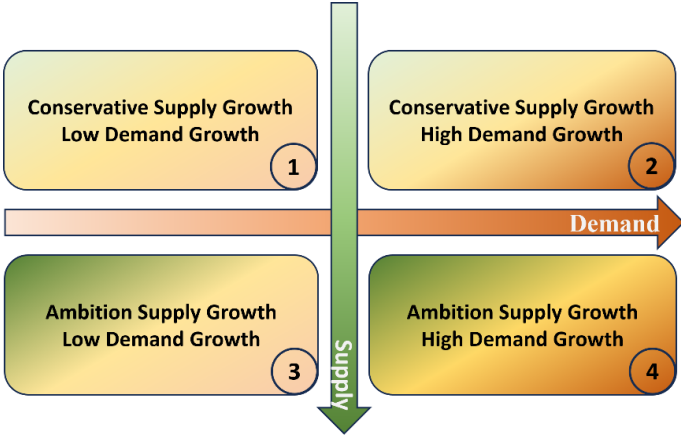
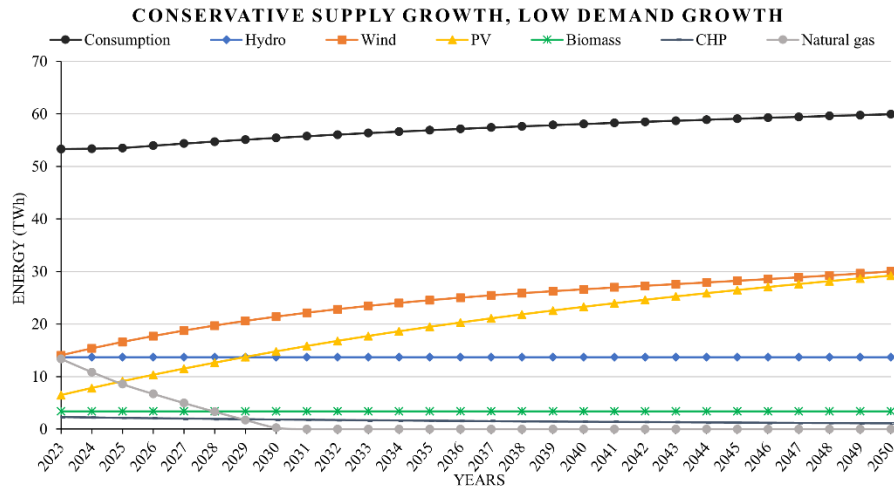


Figure 87 - Scenarios regarding supply and demand

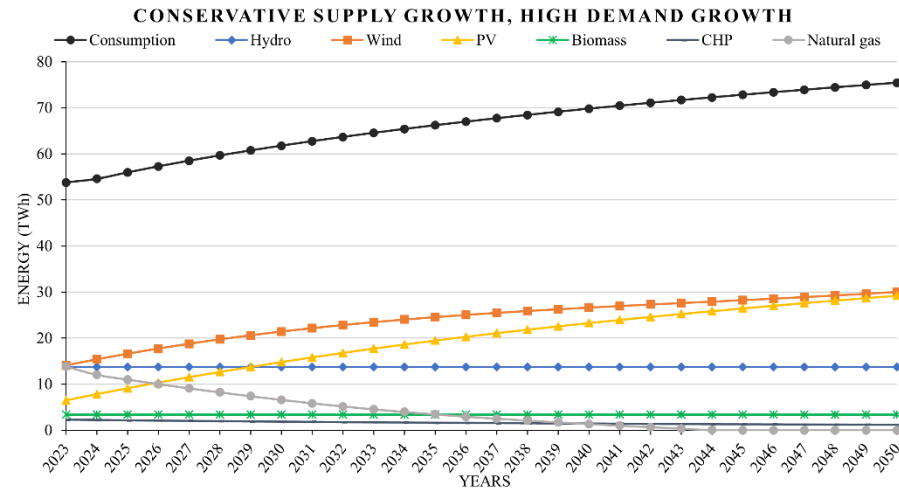
For reasons of simplification, these scenarios will, from now on, be designated by the number shown in the figure.

It is worth noting that the scenarios discussed in the previous sections regarding the evolution of installed generation capacity and electricity consumption cannot be directly compared. Indeed, installed generation capacity is measured in terms of power, while consumption is measured in terms of energy. Additionally, the relationship between installed generation capacity and the energy generated depends on various factors, such as the availability of primary resources like wind or sun. However, typical generation profiles for non-conventional generation units may be used to estimate the energy generated over the years. This procedure allows for depicting the predictions for demand (electricity consumption) and supply (electricity generation) in the same graphs.

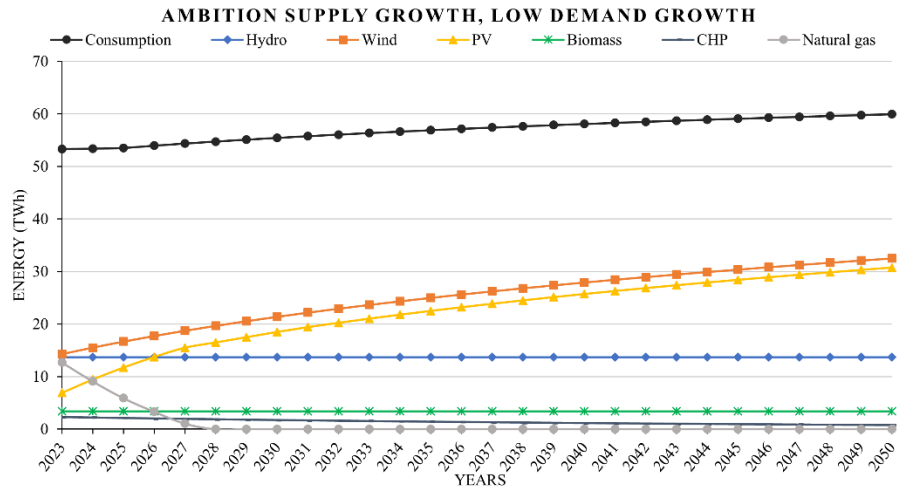
Although generation and consumption profiles will be discussed in subsequent sections, Figure 88 present the annual evolution of electricity generation and consumption for the global scenarios previously presented, until 2050.



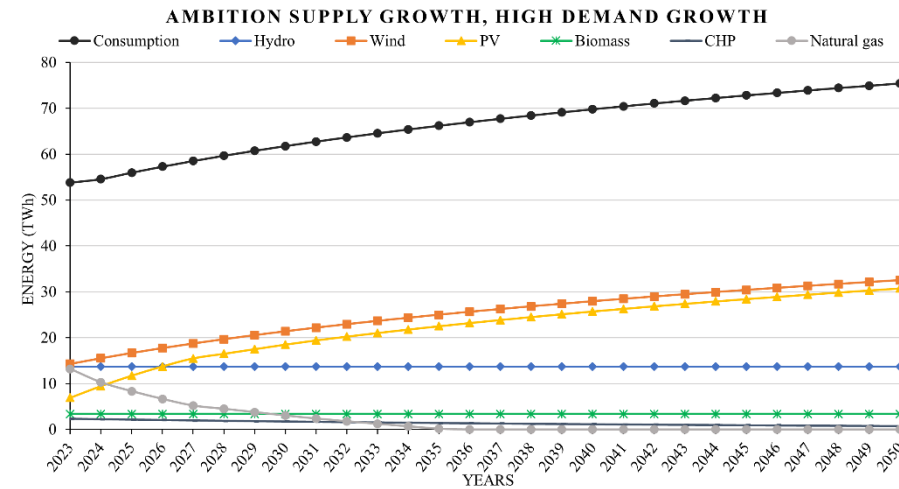
Conservative growth and low increase in consumption scenario



Conservative growth and high increase in consumption scenarios



Ambition growth and low increase in consumption scenario



Ambition growth and high increase in consumption scenario

Figure 88 - Energy prospects of supply and demand sides according to the defined scenarios

5.2.4. Generation and consumption profiles

Estimating accurate avoided emissions requires more than just forecasts for global annual electricity consumption and the annual installed power in non-conventional generation. The alignment between generated electricity and consumption throughout the year plays a vital role in this estimation. It should be noted that a higher level of avoided emissions is usually achieved when there is a greater alignment between electricity consumption and generation.

Therefore, electricity generation and consumption profiles are crucial in applying the methodology developed and presented in Chapter 4 of this work. In this section, the used profiles are described.

5.2.4.1. Generation profiles

The generation profiles for various technology generations were determined by analyzing historical generation data acquired from the Portuguese system operator REN [88]. A sample of this data, specifically the power generated by each technology in 15-minute intervals over a day, is depicted in Figure 89 for reference. In total, 35040 values were collected annually for each generation technology to create their respective profiles.

1	Units: [MW]													
2	Information accessed at: 13/04/2023 09:32:06													
3	Date and Hour	Hydro	Wind	Solar	Biomass	Waves	Natural Gas - Combined cycle	Natural Gas - Cogeneration	Coal	Other Thermal	Import	Export	Pumping	Consumption
4	2022-01-01 00:00:00	718.9	2361	0	418.6	0	0	168.1	0	25	1555	0	608.3	4617.8
5	2022-01-01 00:15:00	711.6	2351.4	0	418.1	0	0	154.9	0	26.2	1641.1	0	705.4	4576.6
6	2022-01-01 00:30:00	629.5	2327.8	0	414.4	0	0	153.4	0	27.1	1668.9	0	649.4	4552.9
7	2022-01-01 00:45:00	527	2306.4	0	417.9	0	0	153.7	0	27.8	1754	0	650.3	4514.8
8	2022-01-01 01:00:00	354.6	2286	0	422.1	0	0	154.6	0	28.3	1926.3	0	670.5	4481.8
9	2022-01-01 01:15:00	261.1	2266.8	0	421.7	0	0	154.9	0	28.7	1982.2	0	655.2	4438.8
10	2022-01-01 01:30:00	255.2	2235.9	0	425.2	0	0	154.3	0	29	2006.7	0	724.7	4361.1
11	2022-01-01 01:45:00	224.6	2223.8	0	420.3	0	0	153.4	0	27.7	2084.7	0	825.7	4284.1
12	2022-01-01 02:00:00	222.8	2200.7	0	421.1	0	0	154.7	0	27.1	2225.9	0	1031.3	4198.1
13	2022-01-01 02:15:00	218.2	2181.4	0	418.6	0	0	154.5	0	27.7	2204.2	0	1054	4128.5
14	2022-01-01 02:30:00	217.8	2168.8	0	419.9	0	0	154.8	0	28.2	2195	0	1103.9	4059.5
15	2022-01-01 02:45:00	219.4	2167	0	420.3	0	0	154.5	0	29.5	2205.6	0	1169.2	4003.3
16	2022-01-01 03:00:00	199.2	2208.4	0	418	0	0	155.2	0	27.2	2160.1	0	1191.6	3954.2
17	2022-01-01 03:15:00	192.9	2257.4	0	418.3	0	0	155.4	0	26.6	2108.8	0	1258.1	3880.5
18	2022-01-01 03:30:00	189.5	2279.9	0	418.4	0	0	154.3	0	27.9	2037.6	0	1257.1	3829
19	2022-01-01 03:45:00	188.3	2303.5	0	418.6	0	0	154.4	0	27.5	1983.6	0	1264.8	3788.5
20	2022-01-01 04:00:00	187.9	2338.6	0	415.4	0	0	154.5	0	27.3	2060.9	0	1402.2	3760.3
21	2022-01-01 04:15:00	189	2380.1	0	414.4	0	0	154.9	0	27.2	2050.1	0	1454.3	3738.3
22	2022-01-01 04:30:00	188	2406.4	0	412	0	0	154.5	0	25.8	2063.6	0	1516.7	3710.2
23	2022-01-01 04:45:00	188.1	2443.2	0	414.3	0	0	153.2	0	25.4	2005.2	0	1516.9	3690.5
24	2022-01-01 05:00:00	224.9	2472.5	0	412.8	0	0	152.8	0	26.5	2022.3	0	1606.9	3681.5
25	2022-01-01 05:15:00	232.9	2457.2	0	414.6	0	0	154.2	0	27	2012.1	0	1609.4	3665.9
26	2022-01-01 05:30:00	231.1	2430.5	0	420	0	0	154.2	0	27.1	2026.6	0	1609.6	3659.6
27	2022-01-01 05:45:00	252	2440.3	0	424	0	0	153.9	0	27.1	1994.4	0	1615.9	3655.4
28	2022-01-01 06:00:00	357	2448.2	0	414.4	0	0	154.4	0	26.9	1983	0	1685.7	3677.5
29	2022-01-01 06:15:00	368.8	2466.4	0	418.9	0	0	155.2	0	28.7	1948	0	1699.1	3666.4

Figure 89 - Data acquired from the system's operator – example for 2022

Data from the six years from 2017 to 2022 was considered for defining the generation profiles of wind, PV, CHP, and biomass technologies. The generation profiles for these technologies were derived by calculating the average generation value at each 15-minute interval throughout those years. This approach allowed for the creation of typical generation profiles for each technology in 15-minute intervals.

In the case of hydropower, a similar procedure was used. However, because 2017 was a particularly dry year, the generation data of this year was excluded from the averaging process. Therefore, only data from the five years between 2018 and 2022 was used to define this technology’s generation profile.

Figure 90 to Figure 93 display a sample of the obtained generation profiles, specifically highlighting three days from each year’s season. Note that these profiles were established by considering the ratio between the generated and installed power for each generation technology.

The generation profiles provide a way to estimate the expected electricity generation of each technology, taking into account the growth of installed power over time. To accomplish this, we can multiply the installed power of a technology by its corresponding typical production profile for each 15-minute interval of every year. By following this procedure, we can calculate the power generated by each technology during each 15 minutes. Additionally, to convert this power into the corresponding energy value, we can multiply it by 0.25 (since 15 minutes equals 0.25 hours).

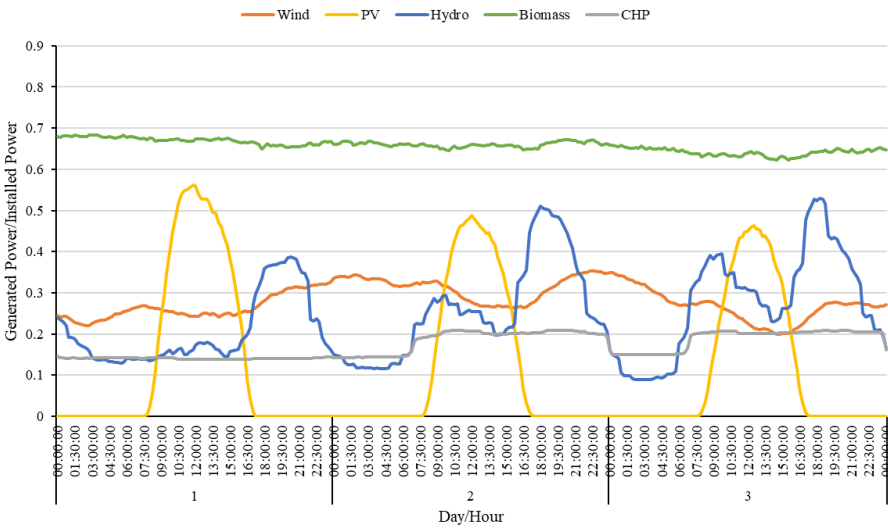


Figure 90 - Generation profiles for three typical days of the winter season (January)

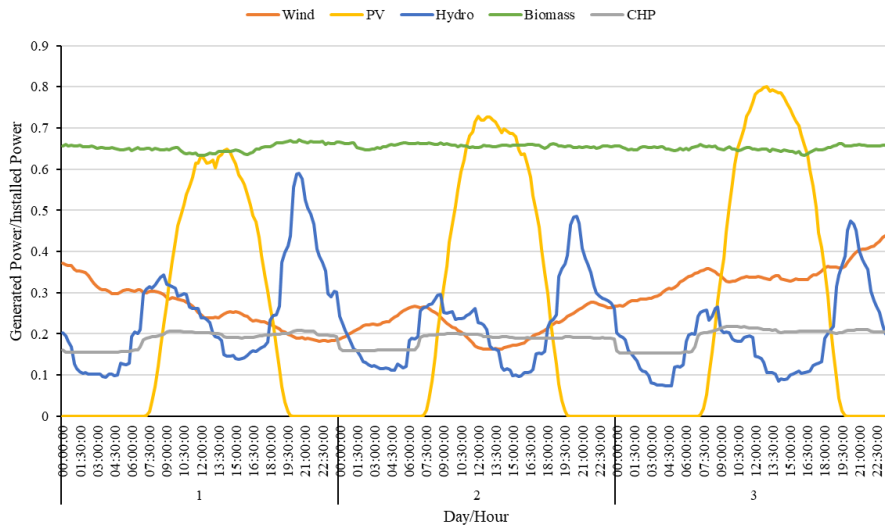


Figure 91 - Generation profiles for three typical days of the spring season (April)

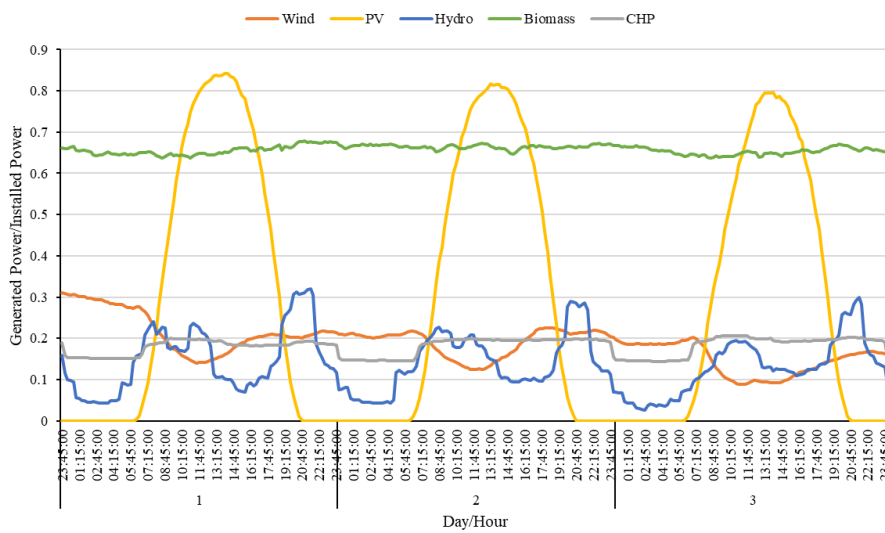


Figure 92 - Generation profiles for three typical days of the summer season (July)

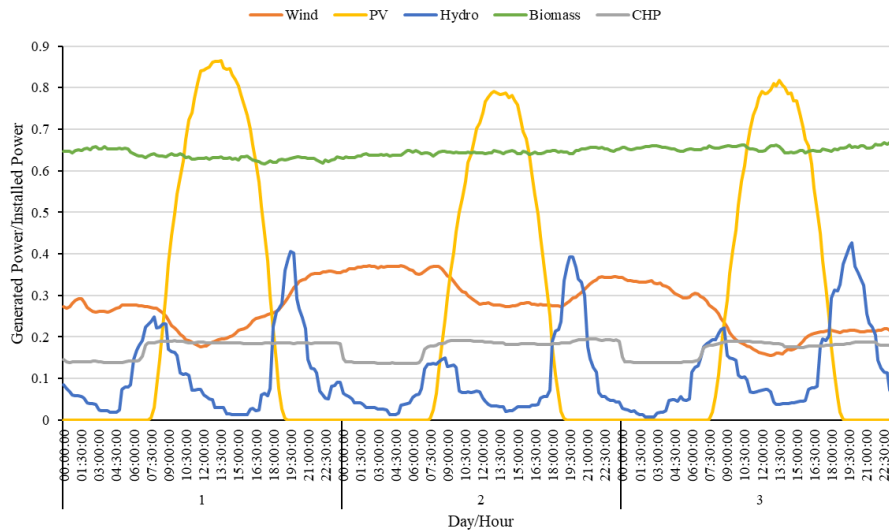


Figure 93 - Generation profiles for three typical days of the fall season (October)

5.2.4.2. Consumption profile

Like the generation profiles, the electrical energy consumption profile is essential when estimating the evolution of emissions from an electrical system. In effect, the consumption profile will allow us to define what part of the total annual consumption occurs in each specific period, in this case, in each annual period of 15 minutes.

The consumption profile can be defined on a permille or percentage basis, being the last adopted in this work. Thus, information on annual electricity consumption in Portugal in periods of 15 minutes was collected from the Portuguese system operator [88]. The years between 2012 and 2022 were considered.

Based on this information, a typical percentual consumption profile for the Portuguese power system was created using a procedure similar to the one mentioned for the generation profile definition. Concretely, the average load was calculated for each period of 15 minutes in the years between 2012 and 2022. The average values were then added together. The percentage profile was then obtained by dividing the average value of each 15 minutes by the sum already mentioned. Figure 94, shows a graph of the obtained consumption profile, in this case, for two specific days.

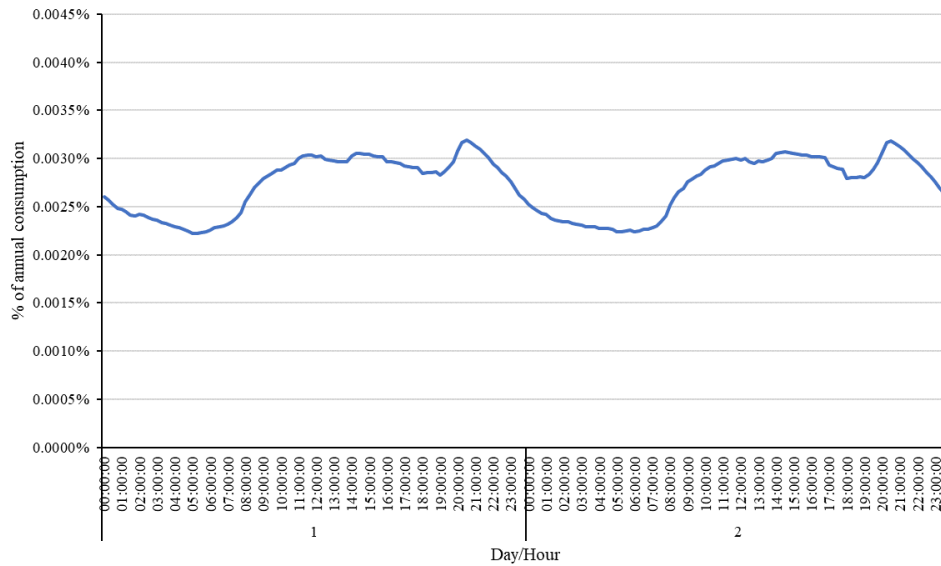


Figure 94 - Consumption profile for two typical days of April

The profile obtained using the method described above is, in this work, called the base consumption profile. However, it is essential to note that this profile may not account for specific situations that could arise from specific electrical loads, which, based on their characteristics, have the potential to alter the base consumption profile significantly.

As mentioned earlier, the usage of electrolyzers for hydrogen production and the rise of data centres (driven by digitalization) will significantly contribute to the growing demand for electricity. It may also contribute to altering the consumption pattern.

Nonetheless, electric mobility is anticipated to drive the most significant impact on the consumption profile. Therefore, the specificities related to the charging periods of electric vehicles appear to deserve special attention due to their potential to change the electricity consumption profile.

Several studies have been conducted to analyse how electric vehicles (EVs) could impact the load profile of the electric power system [99] – [104]. It’s important to note that the specific effects can vary based on factors such as vehicle charging requirements and driver mobility patterns. Figure 95 illustrates three potential profiles for electric vehicle (EV) charging [100]:

1. “Blind” Charge, where most EVs are charged as soon as their owners arrive home after a workday. This approach will likely significantly increase the peak-hour load of electric power systems.

2. Off-peak charging corresponds to the case in which the EVs are charged in off-peak hours. This scenario is the most likely to occur, as electricity supply contracts often offer lower costs during specific periods. Over time, with a substantial increase in EV adoption, this scenario is expected to result in elevated electricity consumption during nighttime hours.
3. Smart Grids and Energy Communities, where advanced technologies can interact with EVs to optimize electricity usage and provide services to the grid [105], [106]. This scenario is ideal once it benefits individual users and enhances grid stability and efficiency.

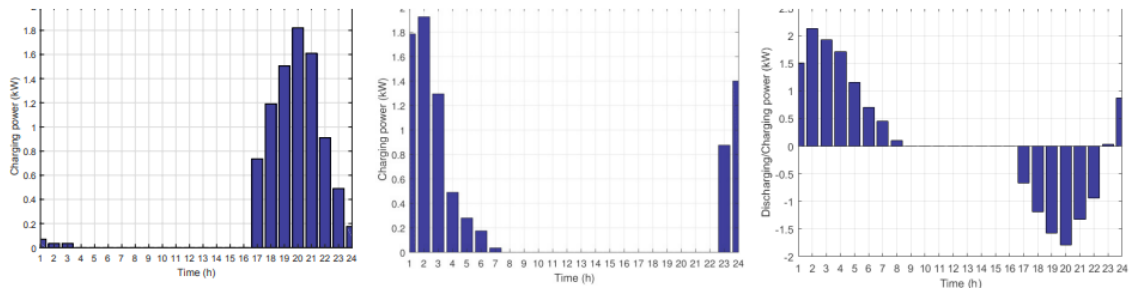


Figure 95 - Potential EV load profiles (uncontrolled on the left, concentrated on the night period in the middle, and with V2G on the right) (Source: [100])

In addition to the profiles for the EV charging process, the impact on the consumption profile is also significantly influenced by the number of electric vehicles in circulation. Figure 96 presents two scenarios for the expected number of electric cars in Portugal obtained according to the above-mentioned documents and entities [92] – [96]. Moreover, according to [107], introducing one million EVs would result in an annual energy consumption increase of approximately 3,160 GWh in the context of the Portuguese electric grid. This amount of energy is equivalent to 6.3% of the electricity consumption verified in 2022 (50.35 TWh).

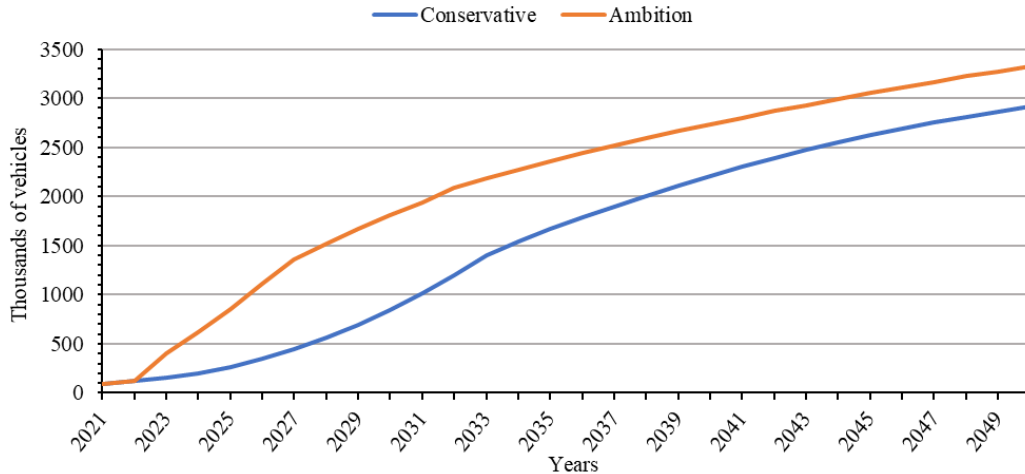


Figure 96 - Forecasting for the number of electric vehicles circulating in Portugal

In this work, two additional consumption profiles were defined to assess how electric mobility could impact the electricity consumption pattern of the system and, subsequently, the resulting emissions. Therefore, the following three consumption profiles were defined:

- A – corresponding to the base consumption profile, as previously defined;
- B – corresponding to the base consumption profile but adjusted to internalise the off-peak charging pattern for EV, and so with increased load demand at the night period;
- C – this corresponds to the base consumption profile but is adjusted to internalise the blind charging pattern of EV, thus, with increased load demand affecting peak hours.

Note that a specific consumption profile was not defined regarding the optimal charging pattern in the context of smart grids and energy communities (we consider that this case is covered by scenario A).

The impact of each charging strategy on the annual base consumption profile was internalized, taking into account the following:

- the forecast for the number of electric vehicles circulating in Portugal as depicted in Figure 96;
- the EV charging patterns outlined in reference [100];
- the electricity consumption for charging electric vehicles as defined in reference [107];

- 70% of electric vehicles will charge during the specified charging periods mentioned in reference [100];
- the daily and annual energy consumption predicted for the base scenario remains unchanged each year, therefore not being affected by the charging strategies adopted for EVs. Therefore, the consumption profiles A, B and C do not affect the overall electricity consumption.

Profiles B and C are derived from profile A by considering the abovementioned assumptions. Firstly, in line with the finding in [107], the provisions on electricity consumption (seen in 5.2.2) and the number of the EV fleet (seen in this section, Figure 96), it was possible to extrapolate the amount of energy from the total yearly consumption that corresponds to the energy that will be used charge the EVs. That amount of energy was then allocated accordingly to the findings in [100] to the respective periods. Finally, the profiles were converted back to percentages to be ready for use. Note that as the provisions for the EV fleet and consumption vary each year and for scenarios. Contrary to the base load profile (profile A), which is always the same and only needs to be adjusted for the expected energy consumption in the study, the profiles B and C vary each year and for each scenario (with low increase in demand and high increase in demand).

Figure 97 to Figure 100 depicts an example of the load behaviour for the three consumption profiles mentioned above. Note that the data refers to three days for each season of the year 2040 for the conservative scenario.

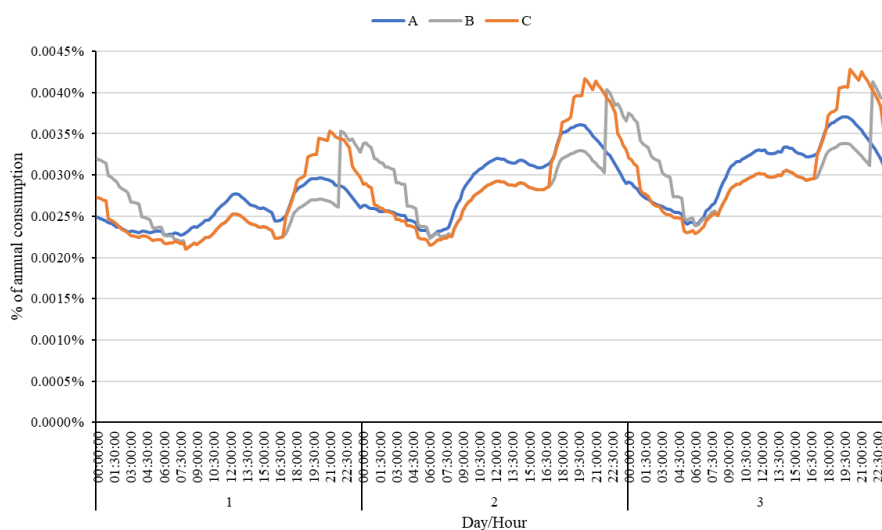


Figure 97 - Load profiles for three typical days of the winter season (January)

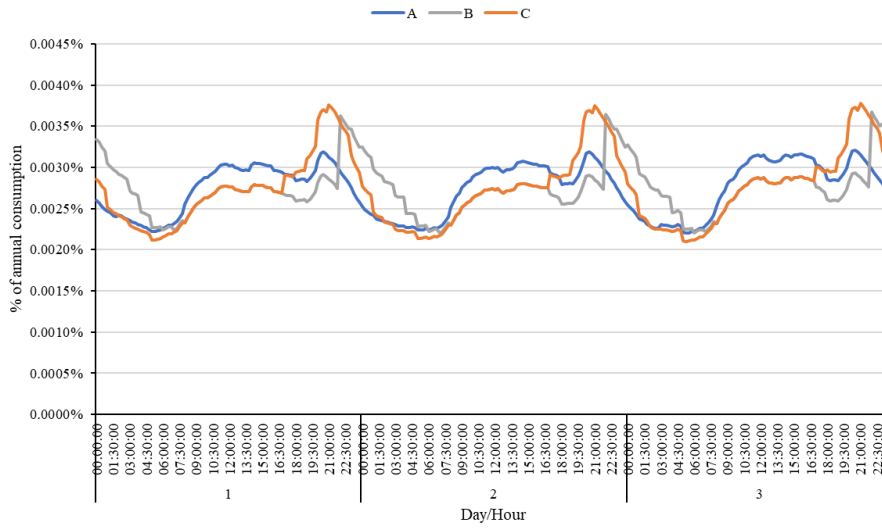


Figure 98 - Load profiles for three typical days of the spring season (April)

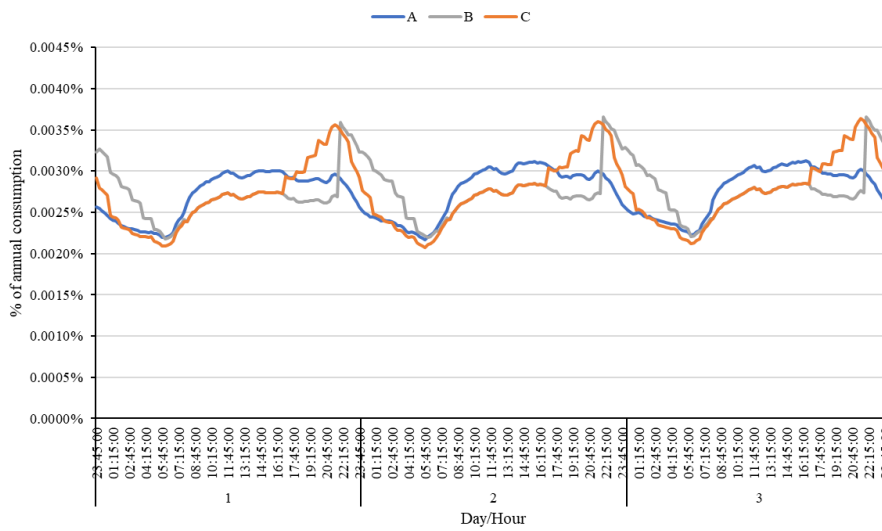


Figure 99 - Load profiles for three typical days of the summer season (July)

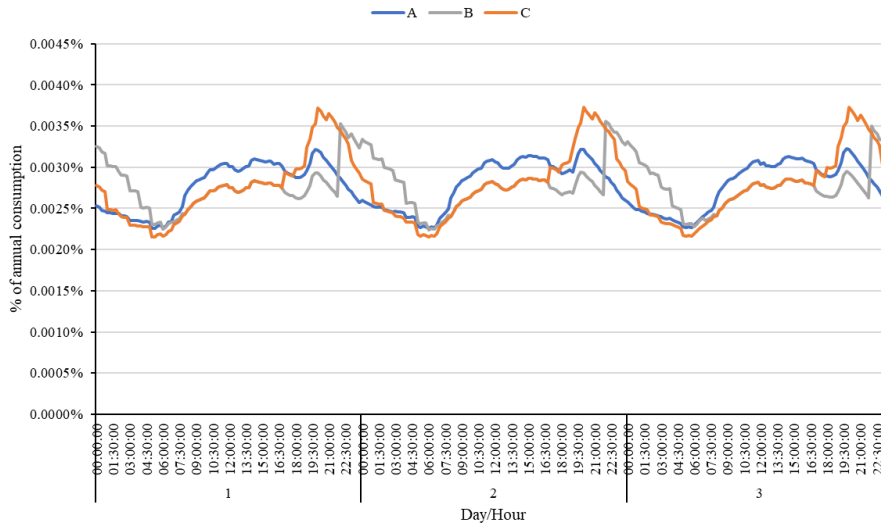


Figure 100 - Load profiles for three typical days of the fall season (October)

5.2.4.3. Impact of profiles on global scenarios

Considering different patterns for EV charging implies, as demonstrated in the previous section, changes to the electricity consumption profile. Therefore, some sub-scenarios may be defined to represent such a situation.

Table 21 summarises the chosen nomenclature for the revised global scenarios. Similarly to what was adopted in section 5.2.3, the assigned letter will refer to the sub-scenarios described in the previous section. For instance, Scenario 2B corresponds to the global scenario characterized by conservative supply growth, a high increase in energy consumption, and a load profile showing increased consumption during the night period due to EV charging.

Table 21 - Summary of the scenarios' nomenclature

Scenario	Supply growth	Demand	Load profile
1A	Conservative	Low	Normal
1B	Conservative	Low	Increased load at the night period
1C	Conservative	Low	Increased load at the peak hours
2A	Conservative	High	Normal
2B	Conservative	High	Increased load at the night period
2C	Conservative	High	Increased load at the peak hours
3A	Ambition	Low	Normal
3B	Ambition	Low	Increased load at the night period
3C	Ambition	Low	Increased load at the peak hours
4A	Ambition	High	Normal
4B	Ambition	High	Increased load at the night period
4C	Ambition	High	Increased load at the peak hours

5.3. Location of generation and consumption across the system

5.3.1. Consumption

The CO₂ emissions are directly affected by where electricity is consumed within the electrical networks. This impact is mainly caused by the losses incurred to meet consumption, which are higher for lower voltage networks, as well as the distance between consumption locations and electricity generation units. Therefore, it is essential to characterize how electricity consumption occurs along electrical networks.

Information on demand characterization reports made available by Energy Services Regulatory Authority (ERSE) [108] – [116] was used to characterize the distribution of consumption across the various voltage levels of the power system. The information shows consumption behaviour per voltage level that is relatively stable over the years. In other words, the percentage of total electricity consumption at each electrical system voltage level over the years has remained approximately constant. Therefore, in this study, the values of Table 22 were assumed.

Table 22 - Energy consumption on the various voltage levels of the power system

	Voltage Level				
	VHV	THV	HV	MV	LV
Consumption		5%	15%	30%	50%

5.3.2. Generation

As in the case of electricity consumption, the location of generation units, particularly non-conventional units, directly influences CO₂ emissions (in particular, emissions that can be avoided). In this context, the greater or lesser proximity to consumption points and electrical energy storage systems are crucial aspects.

Obtaining precise data on the distribution of generation technologies (hydro, wind, PV, CHP, biomass) across various power system voltage levels proved challenging. Nonetheless, the data available from suitable sources [117] – [137] was used to make informed assumptions about the distribution of generation capacity. From those sources, it was possible to infer the following conclusions:

- most installed hydropower capacity is located at the High Voltage level;
- wind power generation is primarily concentrated at the HV level;

- PV generation is distributed across the various voltage levels;
- no relevant information was found for CHP and Biomass.

Therefore, the distribution shown in Table 23 was adopted concerning the location of non-conventional generation.

Table 23 - Location of generation technologies across the various voltage levels of the electric system

	Voltage Level				
	VHV	THV	HV	MV	LV
Hydro	18%	72%	10%		
Wind			95%	5%	
PV		10%	50%	30%	10%
Biomass			100%		
CHP			100%		

The distribution depicted in Table 23 is expected to fluctuate over time. Nevertheless, it was assumed to remain constant for the purposes of this study. However, a sensitivity analysis on this topic will be assessed later.

5.4. Loss factors

In this work, two loss factors are accounted for: the average loss factors and the average avoided loss factors.

The average loss factors, denoted by $\gamma_{\Delta t}$ in Chapter 4, accounts for the energy lost on the transmission and distribution networks when it is transferred from generation to consumption points. Those factors may be defined using the information on the annual loss adjustment factors (LAF) provided by the Portuguese Regulator (ERSE) [138]. Figure 101 shows an extract of the LAF defined by ERSE for the year 2023. As can be seen from the figure, the adjustment factors for losses are percentual values and are broken down by electrical network/voltage level and by 15-minute periods. Therefore, the consumption of 1 kWh of electricity in the LV networks that comes from the VHV network at a specific period Δt , implies a loss value of $1 \times (1 + \gamma_{\Delta t}^{LV}) \times (1 + \gamma_{\Delta t}^{MV}) \times (1 + \gamma_{\Delta t}^{HV}) \times (1 + \gamma_{\Delta t}^{THV}) \times (1 + \gamma_{\Delta t}^{VHV}) - 1$ kWh.

Date	Day	Hour	Loss Adjustment Factors				
			LV	MV	HV	THV	VHV
1/jan/2023	sun	00:15	0.093277	0.035119	0.012677	0.018561	0.013920
1/jan/2023	sun	00:30	0.090197	0.034540	0.012500	0.018561	0.013920
1/jan/2023	sun	00:45	0.087353	0.033832	0.012283	0.018561	0.013920
1/jan/2023	sun	01:00	0.084362	0.033128	0.012067	0.018561	0.013920
1/jan/2023	sun	01:15	0.081437	0.032382	0.011836	0.018561	0.013920
1/jan/2023	sun	01:30	0.078573	0.031664	0.011610	0.018561	0.013920
1/jan/2023	sun	01:45	0.075762	0.031021	0.011408	0.018561	0.013920
1/jan/2023	sun	02:00	0.072981	0.030398	0.011218	0.018561	0.013920
1/jan/2023	sun	02:15	0.070432	0.029804	0.011040	0.017474	0.013106
1/jan/2023	sun	02:30	0.068018	0.029246	0.010869	0.017474	0.013106
1/jan/2023	sun	02:45	0.065882	0.028770	0.010721	0.017474	0.013106
1/jan/2023	sun	03:00	0.063911	0.028336	0.010584	0.017474	0.013106
1/jan/2023	sun	03:15	0.062210	0.027953	0.010462	0.017474	0.013106
1/jan/2023	sun	03:30	0.060592	0.027589	0.010345	0.017474	0.013106
1/jan/2023	sun	03:45	0.059310	0.027300	0.010254	0.017474	0.013106
1/jan/2023	sun	04:00	0.058223	0.027059	0.010179	0.017474	0.013106
1/jan/2023	sun	04:15	0.057399	0.026888	0.010125	0.017474	0.013106
1/jan/2023	sun	04:30	0.056636	0.026731	0.010078	0.017474	0.013106
1/jan/2023	sun	04:45	0.056098	0.026617	0.010046	0.017474	0.013106
1/jan/2023	sun	05:00	0.055671	0.026540	0.010019	0.017474	0.013106
1/jan/2023	sun	05:15	0.055352	0.026510	0.010001	0.017474	0.013106
1/jan/2023	sun	05:30	0.054987	0.026475	0.009979	0.017474	0.013106
1/jan/2023	sun	05:45	0.054668	0.026449	0.009967	0.017474	0.013106

Figure 101 - Extract of values for the loss adjustment factors – example for 2022

It is important to emphasize that while LAF may fluctuate over the years, these factors have remained reasonably steady, as shown in Figure 102 for the case of full hours period. Indeed, only one variation in LAF occurred over the last eight years (concretely in 2022) and was relatively minor in size, being more significant in the LV networks case.

Therefore, in this work, the loss factors established by the regulator for 2023 were considered [139]. Moreover, the LAF values were assumed to remain constant throughout the study period.

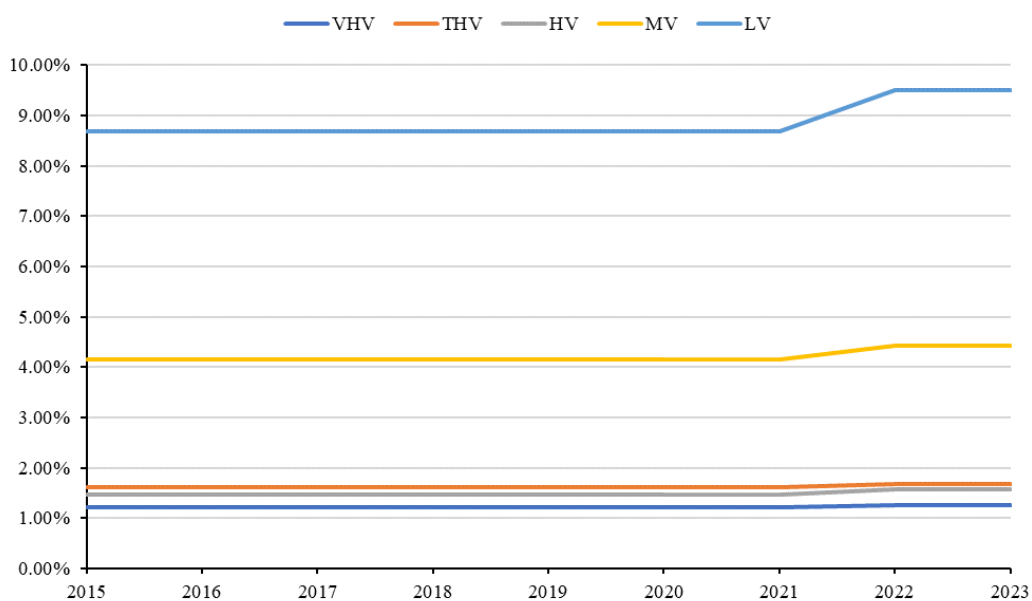


Figure 102 - Evolution of the LAF for the peak period (2015-2023)

The average avoided loss factors, denoted as $\delta_{\Delta t}$ in Chapter 4, allows to quantify the avoided electricity losses due to the action of the electricity generation near the consumption points. In practice, those factors allow for quantifying the energy which generation is avoided due to the avoided network losses.

At this point, it is essential to remember that network losses are of two types: variable losses and fixed losses. The variable losses depend on the amount of energy flowing in the networks, and it's correlated with the LAF. The fixed losses consider the losses in the transformers' magnetic cores and the cables' dielectric losses (and so, these losses are not influenced by the action of distributed generation).

As described in [140], the avoided losses factors may be calculated by:

$$\delta_{p,\Delta t} = \frac{1 + \gamma_{p,\Delta t}}{\sqrt{\gamma_{p,\Delta t}^2 + 2\gamma_{p,\Delta t} \times (2\zeta_{p,\Delta t} - 1) + 1}} - 1 \quad (47)$$

Where: $\delta_{p,\Delta t}$ is the avoided loss factor for network p in period Δt ;

$\gamma_{p,\Delta t}$ is the loss adjustment factor for network p in period Δt ;

$\zeta_{p,\Delta t}$ is the percentage of total losses that correspond to fixed losses for network p in period Δt .

The values adopted for the $\zeta_{p,\Delta t}$ parameters are presented in Table 24, and were assumed accordingly to [140].

Table 24 - Percentage of total losses that are fixed losses

	Time period (Δt)			
	Peak	Full	Empty	Super empty
$\xi_{VHV}^{\Delta t}$	12%	20%	25%	30%
$\xi_{THV}^{\Delta t}$	12%	20%	25%	30%
$\xi_{HV}^{\Delta t}$	12%	20%	25%	30%
$\xi_{MV}^{\Delta t}$	12%	20%	25%	30%
$\xi_{LV}^{\Delta t}$	12%	20%	25%	30%

It is essential to highlight that the losses avoided in a network p by a generator located in that same network do not correspond to the total losses of that network. Indeed, the avoided losses will depend on the generation and consumption location points, as explained in [140], [141]. Therefore, a suitable factor that measures the expected avoided losses for those cases needs to be used. Table 25 shows the values (k factors) assumed in this work, obtained from [140].

Table 25 - Assumed values for the k factor

	Time period (Δt)			
	Peak	Full	Empty	Super empty
k	0.60	0.47	0.31	0.115

Note that as the LAF values are presented for periods of 15 minutes, the average avoided loss factors have also been computed for 15-minute periods. Figure 103 shows an extract of the values considered in this work for the avoided loss factors.

Date	Hour	VHV	THV	HV	MV	LV
1/jan/2023	00:15:00	0.020952	0.027966	0.019075	0.053115	0.142665
1/jan/2023	00:30:00	0.020952	0.027966	0.018807	0.052233	0.137884
1/jan/2023	00:45:00	0.020952	0.027966	0.01848	0.051154	0.133473
1/jan/2023	01:00:00	0.020952	0.027966	0.018154	0.050082	0.128836
1/jan/2023	01:15:00	0.020952	0.027966	0.017805	0.048947	0.124305
1/jan/2023	01:30:00	0.020952	0.027966	0.017464	0.047853	0.119873
1/jan/2023	01:45:00	0.020952	0.027966	0.01716	0.046875	0.115526
1/jan/2023	02:00:00	0.019514	0.026028	0.015722	0.042666	0.102632
1/jan/2023	02:15:00	0.01837	0.024503	0.015472	0.041832	0.099041
1/jan/2023	02:30:00	0.01837	0.024503	0.015232	0.041046	0.09564
1/jan/2023	02:45:00	0.01837	0.024503	0.015024	0.040377	0.092632
1/jan/2023	03:00:00	0.01837	0.024503	0.014833	0.039767	0.089856
1/jan/2023	03:15:00	0.01837	0.024503	0.014661	0.039227	0.087459
1/jan/2023	03:30:00	0.01837	0.024503	0.014498	0.038716	0.08518
1/jan/2023	03:45:00	0.01837	0.024503	0.01437	0.038309	0.083373
1/jan/2023	04:00:00	0.01837	0.024503	0.014265	0.037972	0.081843
1/jan/2023	04:15:00	0.01837	0.024503	0.014189	0.037731	0.080682
1/jan/2023	04:30:00	0.01837	0.024503	0.014123	0.037509	0.079606
1/jan/2023	04:45:00	0.01837	0.024503	0.014077	0.037349	0.078849
1/jan/2023	05:00:00	0.01837	0.024503	0.014041	0.037242	0.078247
1/jan/2023	05:15:00	0.01837	0.024503	0.014015	0.037198	0.077797
1/jan/2023	05:30:00	0.01837	0.024503	0.013984	0.03715	0.077284
1/jan/2023	05:45:00	0.01837	0.024503	0.013967	0.037113	0.076834
1/jan/2023	06:00:00	0.019727	0.026323	0.015011	0.039971	0.082769

Figure 103 - Extract of the calculated avoided losses factors

5.5. Emission factors

Emission factors are another essential parameter in quantifying the emissions of the electrical system.

The emission factors used in this work were obtained and applied according to [142], adopting the median value. Therefore, Table 26 shows the emission factors for each technology considered in the study.

As explained in Chapter 4, only direct emissions were considered for the generated energy of conventional power plants (natural gas in this study). The emissions considering the Life Cycle Assessment (LCA)⁴ were considered for the remaining generating units.

Table 26 - Assumed emission factors

Technology	Emission factor (kgCO ₂ /MWh)
Natural gas	370
Hydropower	24
Wind	12
PV	48
CHP	370
Biomass	230

The emission factors presented in Table 26 will be used to calculate the effective avoided losses as explained in Chapter 4, section 4.2, and more precisely used to calculate the parameters $f_{\Delta t}$ and e .

To clarify, let us assume the example of Figure 104, where, for the sake of simplicity, only one network and one Δt period were considered.

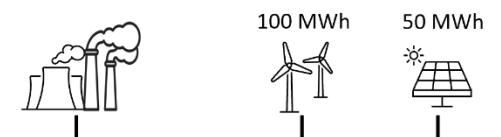


Figure 104 - Example of generation for emission factor calculation

⁴ Life cycle analysis (LCA) is a method of quantifying the environmental impacts associated with a given product. In LCA, researchers create an inventory of resources used and pollutants generated in product production and use. From this, an impact assessment estimates the product's ultimate effects on human health, ecosystem function, and natural resource depletion [162].

The avoided emissions of not generating 1 MWh of electricity in conventional power plants (natural gas-fired plants for the Portuguese situation) will correspond to 370 kg CO₂. Therefore, in this case, $e = 370 \text{ kgCO}_2/\text{MWh}$.

The calculation of the avoided emission factor for the mix of non-conventional generation ($f_{\Delta t}$) must be done following the procedure outlined in section 4.2. Figure 104 shows that 100 MWh of wind energy and 50 MWh of PV generation occur in the period considered. Therefore, the proportion of generation of each technology in period Δt (equation (5)) equals $\frac{100}{100+50} = 66.7\%$ for wind generation and $\frac{50}{100+50} = 33.3\%$ for PV generation. By using equation (4), we can calculate the emission factor for the mix of non-conventional generation in period Δt (the parameter $f_{\Delta t}$) which equals $12 \times 0.667 + 48 \times 0.333 = 23.988 \text{ kgCO}_2/\text{MWh}$. Therefore, the avoided emission factor for the mix of non-conventional generation to be used on the assumed period Δt equals $e_{\Delta t} - f_{\Delta t} = 370 - 23.988 = 346.012 \text{ kgCO}_2/\text{MWh}$.

5.6. Storage systems

A relevant objective of this work is to try to understand the impact of energy storage on emissions from the Portuguese electrical system. Indeed, energy storage can enhance the utilization of energy generated from non-conventional sources by storing surplus energy that occurs in some periods for posterior use. This behaviour may reduce the need for energy generation in conventional power plants, which typically have higher emissions. Additionally, it can reduce the amount of energy lost during transmission to consumption points.

The data available on the installed capacity for energy storage is currently quite limited, and unfortunately, there is a lack of information regarding its distribution across networks. However, despite this limitation, this study aims to analyse the impact of storage on emissions in the Portuguese electricity system. A range of installed storage capacities varying between 0 and 1 TWh for each year and scenario was considered to achieve this objective. By utilizing 3D charts, meaningful insights and conclusions may be drawn from the analysis.

The values presented in Table 27 were assumed as the basis for distributing the storage capacity through the grid. Moreover, a sensitivity analysis will be conducted to evaluate the impact of different distributions.

Table 27 - Distribution of storage capacity through the various voltage levels – Base situation

	Voltage Level				
	VHV	THV	HV	MV	LV
Storage			40%	30%	30%

Currently, the most common storage systems are lithium-based batteries. Hence, for this study, we have considered this technology. However, it is essential to acknowledge that the model described in Chapter 4 does not necessarily rely on this assumption, and other storage technologies can also be employed.

For storage systems' charging and discharging cycle, an efficiency of 97% each is assumed, resulting in a global charging-discharging efficiency cycle of 94.1%. The maximum depth of discharge (DOD) was set at 80%. Additionally, it has been assumed that the battery can reach a full charge/discharge within a 2-hour time frame (and so, the charge/discharge rated power equals half of the storage capacity).

5.7. Results

5.7.1. System with the base consumption profile and without storage

Figure 105 displays the forecasted annual avoided emissions in the Portuguese electrical system when the base consumption profile is considered (i.e. the load of electric vehicles is not concentrated in a specific period).

The scenario with high demand growth and ambitious growth in non-conventional generation capacity (scenario 4A) yields higher expected values of avoided annual emissions over the study period. In this scenario, the expected avoided emissions equals 8 MtonsCO₂ in 2030 and 12.9 MtonsCO₂ in 2050. The accumulated expected avoided emissions from 2023 to 2050 equals 266.5 MtonsCO₂. Conversely, the scenario with low demand growth and conservative growth in non-conventional generation capacity (scenario 1A) shows the lowest potential of avoided expected emissions. For this scenario, the expected avoided emissions equals 6.9 MtonsCO₂ in 2030 and 9.6 MtonsCO₂ in 2050. The accumulated value of expected avoided emissions from 2023 to 2050 equals 214.2 MtonsCO₂, 19.6% lower than the value of Scenario 4A. Moreover, it is visible that the scenarios with high expected increases in electricity consumption (2A and 4A) present higher values of expected avoided emissions.

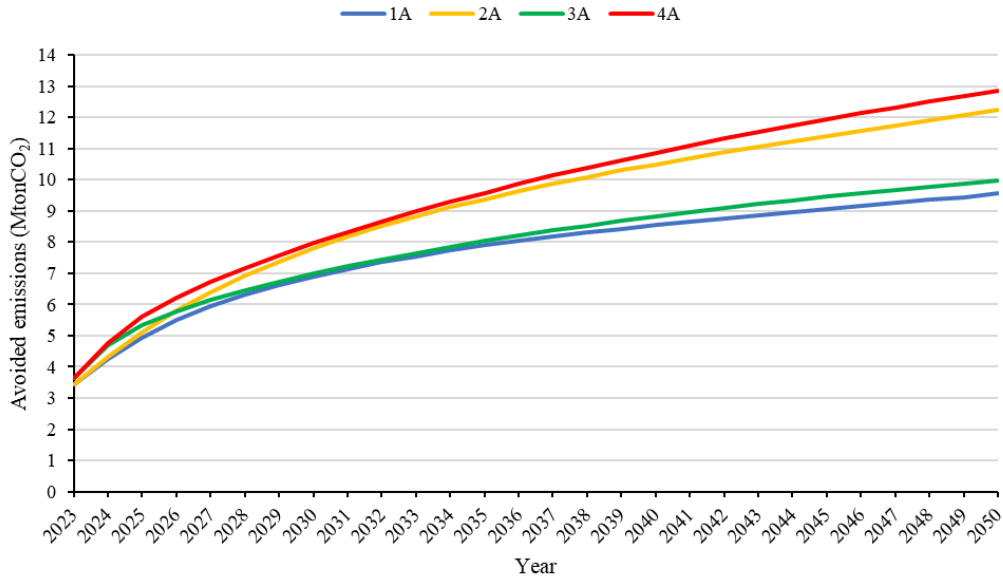


Figure 105 - Expected avoided emissions – scenarios 1A, 2A, 3A and 4A

The findings in Figure 105 also indicate that the expected rate of avoided emissions growth decreases as time progresses, with this trend being more prominent in scenarios with smaller increases in energy consumption (specifically, scenarios 1A and 3A). This situation implies that the dominance of natural gas in power generation is diminishing due to the growing prominence of non-conventional power plants. This effect is less noticeable in high-consumption scenarios (scenarios 2A and 4A), where the annual amount of avoided emissions increases at a higher rate.

5.7.2. System with the base consumption profile and storage

Incorporating storage systems has the potential to enhance avoided emissions. Thus, this section evaluates the impact of energy storage on the value of avoided emissions by comparing values obtained with different installed storage capacities against the scenario with no installed storage systems.

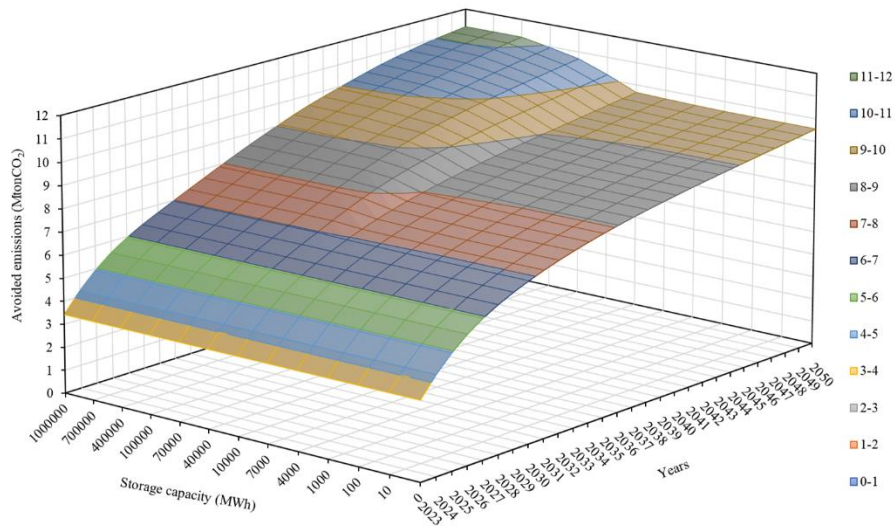
Figure 106 shows the results obtained in the simulations. The simulations assumed that the various storage capacity values were installed in the initial year of the study period. While this assumption does not align with reality, as capacity is typically installed gradually over time, this analysis still provides valuable insights. Indeed, this analysis may determine the optimal storage capacity to be installed over the years.

As can be observed, no matter the scenario considered, the impact of storage systems is minimal for installed capacities up to 10 GWh. Furthermore, it is worth noting that the impact of storage on avoided emissions during the initial years of the study period is minimal, regardless of the installed capacity. This situation is because the installed capacity of non-conventional generation remains relatively low, resulting in limited generation surpluses being stored.

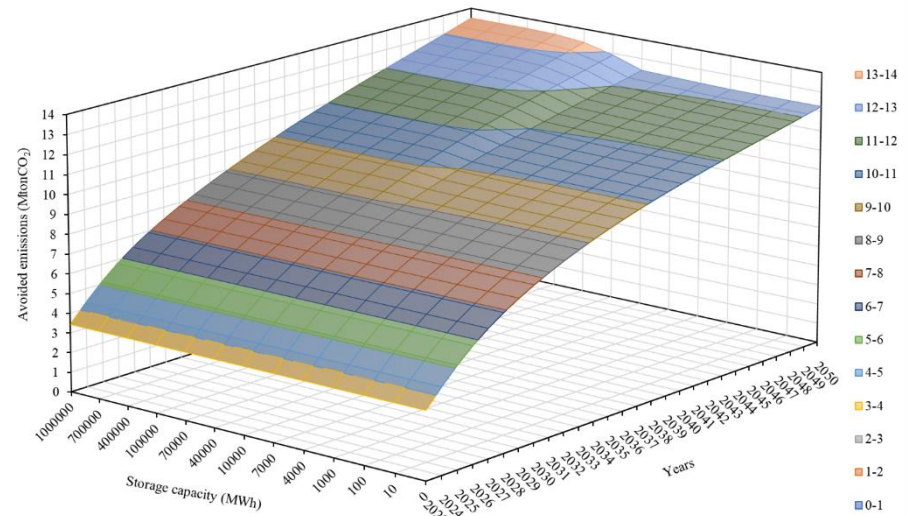
According to the scenario, the impacts of storage systems on avoided emissions can vary significantly. In scenario 1A, the storage systems contribute to an annual increase in avoided emissions ranging from 1% to 17.1%, with their effects beginning in 2032. In scenario 2A the variation ranges from 1% to 10%, starting in 2039. Scenario 4A's variation ranges from 1% to 12.4%, starting in 2032. For scenario 3A, an annual increase in avoided emissions from 1% to 14.6% is forecasted, starting in 2028. However, it is essential to note that the positive effect on avoided emissions for scenarios 1A, 3A, and 4A does not continue to increase beyond an installed capacity of 400 GWh. Similarly, in the case of scenario 2A, this effect plateaus at an installed capacity of 100 GWh.

The scenarios representing low-demand growth (scenarios 1 and 3) show the highest potential for gains by implementing storage systems. By deploying 400 GWh in 2050, these scenarios could experience a substantial increase in avoided emissions, ranging from approximately 14.6% to 17.1%. Conversely, in the same terms, the gains in avoided emissions for the cases of high-demand scenarios (scenarios 2 and 4) range from around 10% to 12.4%.

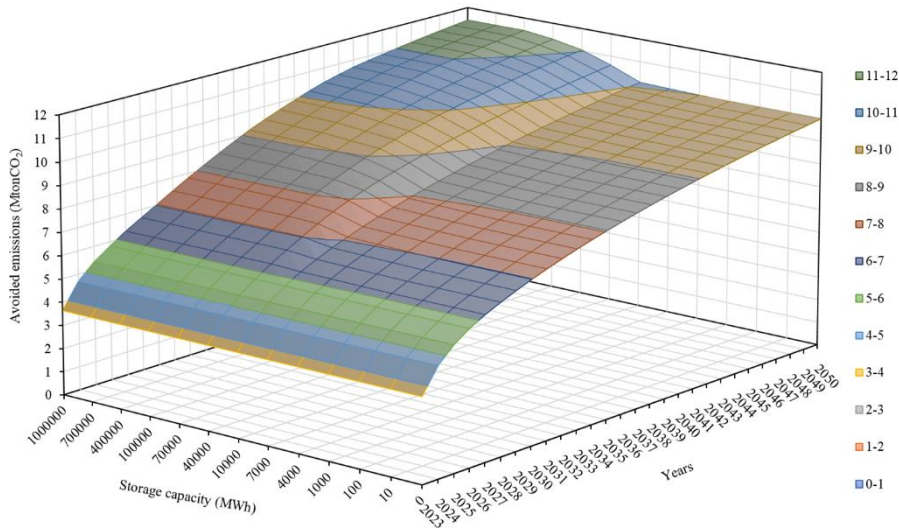
Regarding absolute values of expected avoided emissions, scenario 4A remains the one with the highest yield in expected avoided emissions. If 400 GWh of storage capacity was considered, the avoided emissions in 2050 would be 14.5 MtonsCO₂, with the accumulated expected avoided emissions from 2023 to 2050 becoming 285.7 MtonsCO₂. In the same terms, scenario 1A remains the one showing the least potential, with a result in 2050 of 11.2 MtonsCO₂. The accumulated expected avoided emissions from 2023 to 2050 equals 235.7 MtonsCO₂.



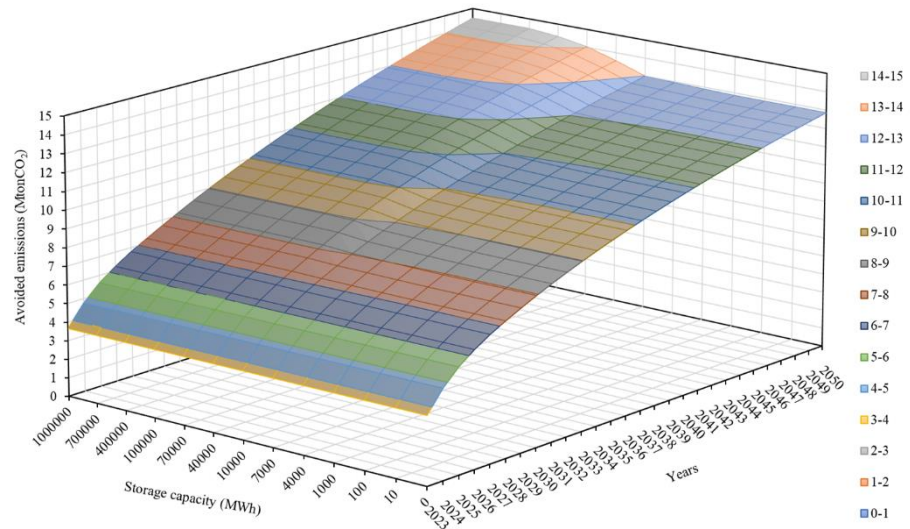
Results of avoided emissions for scenario 1A



Results of avoided emissions for scenario 2A



Results of avoided emissions for scenario 3A



Results of avoided emissions for scenario 4A

Figure 106 - Results of avoided emissions for scenarios 1A, 2A, 3A and 4A when storage capacity is considered

To enhance the clarity of the findings, we have created two-dimensional graphs that compare the benefits of incorporating storage systems in terms of avoided emissions. These graphs present the avoided emissions values for various scenarios, including situations without storage and with installed storage capacities of 10 GWh and 400 GWh. The 10 GWh capacity was chosen as it represents the threshold at which the storage effect becomes noticeable. The 400 GWh capacity was selected as the upper limit for installed capacity, beyond which additional capacity does not yield further gains in avoided emissions. It is important to note that, for scenario 2A, the limit differs and corresponds to 100 GWh instead of 400 GWh, as mentioned earlier.

In Figure 107, for scenario 1A, it becomes evident that the divergence of the curves occurs around 2032, indicating that the implementation of storage becomes beneficial only after this point in time. In this scenario, a storage capacity of 400 GWh results in an additional avoidance of 1.2 MtonCO₂ by 2040 and 1.6 MtonCO₂ by 2050. Note that the gains of avoided emissions originated by a storage capacity of 10 GWh is very limited.

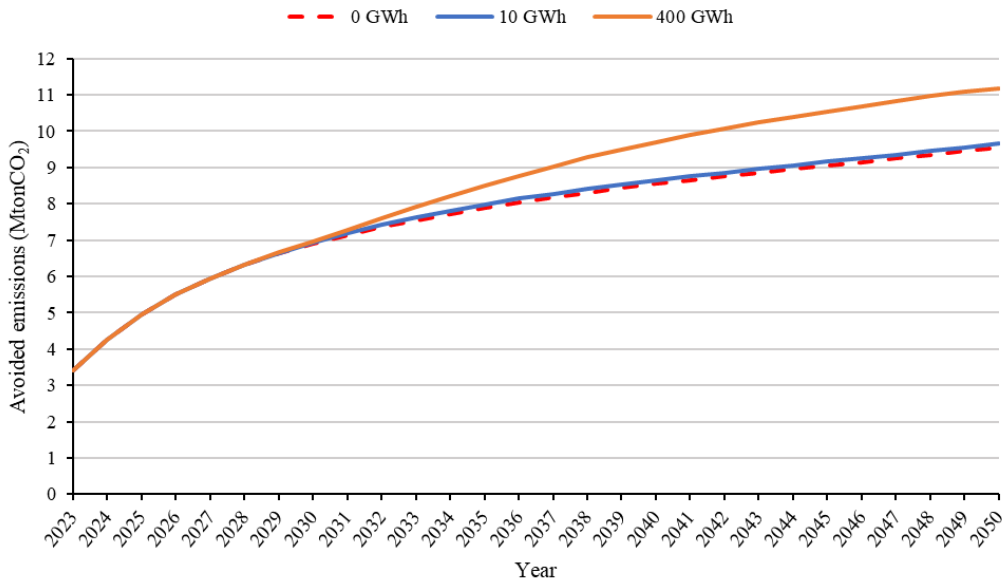


Figure 107 - Avoided emissions for scenario 1A – Storage capacity of 0, 10 and 400 GWh

Figure 108 shows the results for scenario 2A, where the upper limit considered for the storage capacity was 100 GWh (as explained before). In this scenario, the positive effects of storage on avoided emissions only start occurring after around 2039. A storage capacity of 100 GWh allows an amount of additional avoided emissions of 1.2 MtonCO₂ by 2050.

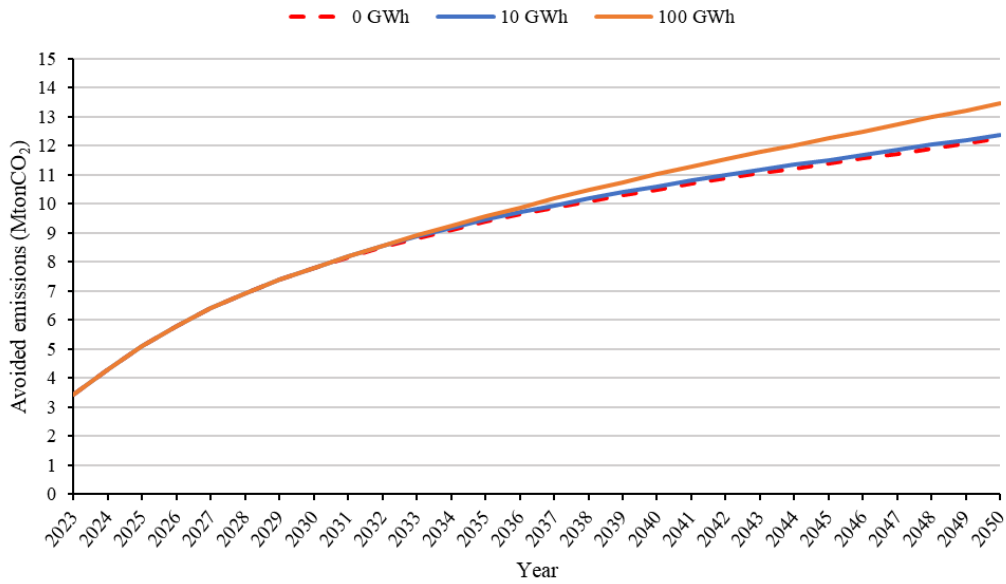


Figure 108 - Avoided emissions for scenario 2A – Storage capacity of 0, 10 and 400 GWh

In relation to scenario 3A, Figure 109 demonstrates the advantages of implementing storage systems from 2028 onwards. With a storage capacity of 400 GWh, achieving an extra reduction of 1.5 MtonCO₂ emissions is possible by 2040. By 2050, the cumulative additional reduction in emissions from the 400 GWh storage capacity will reach a significant total of 11.4 MtonCO₂.

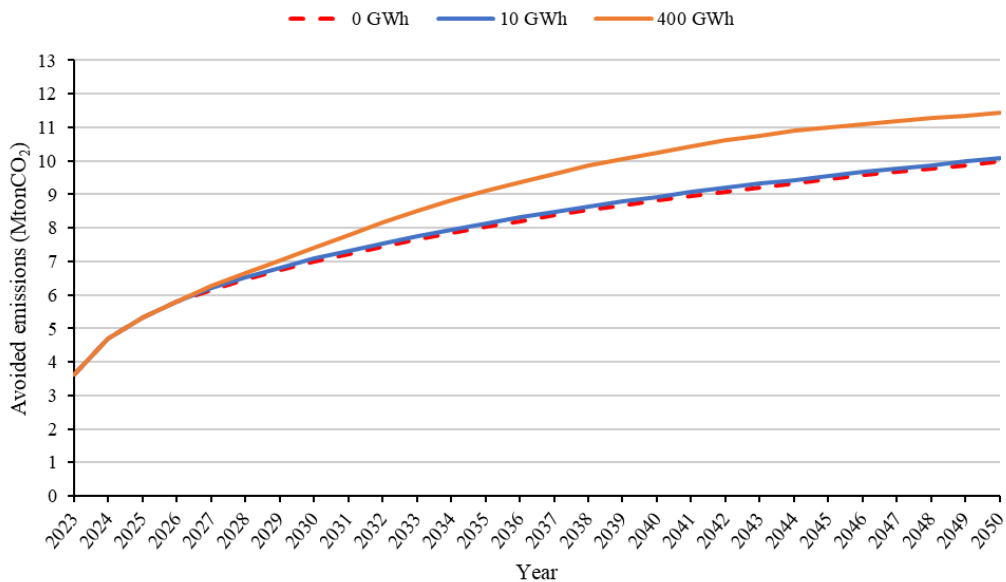


Figure 109 - Avoided emissions for scenario 3A – Storage capacity of 0, 10 and 400 GWh

Figure 110 shows the results for the case of the scenario 4A. In this scenario, the positive effects of the storage systems start after 2032. In 2040, an additional 1 MtonCO₂ can be achieved when 400 GWh of storage capacity exists. This value will increase to 1.6 MtonCO₂ by 2050.

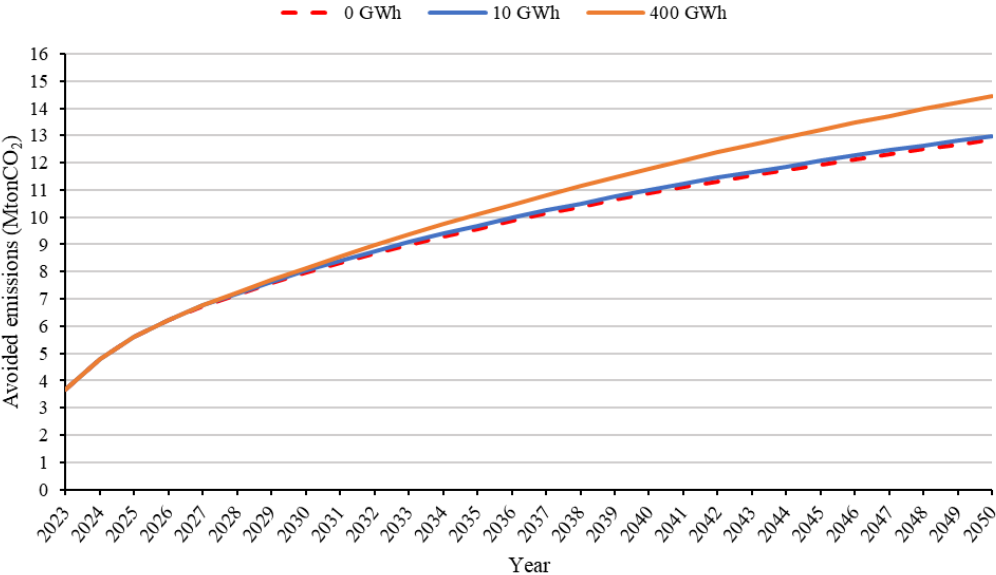


Figure 110 - Avoided emissions for scenario 4A – Storage capacity of 0, 10 and 400 GWh

After closely analysing the graphs in Figure 107 through Figure 110, it is clear that the impact of storage systems on reducing emissions is heavily dependent on the specific scenarios being considered. A key finding is that storage systems yield more favourable outcomes in scenarios where there is a higher surplus of energy. This implies that scenarios which prioritize increased unconventional generation and lower growth in electricity consumption amplify the significance of storage systems in reducing emissions.

As previously mentioned, the results in Figure 106 may be used to estimate the optimal storage capacity that should be installed over the years to maximize the avoided emissions. In practical terms, acquiring this information involves examining the points with the highest value of annual avoided emissions. By conducting this analysis, we gain insights into the corresponding storage capacity, which makes it possible to depict the evolution of optimal storage capacity over the years, as shown in Figure 111.

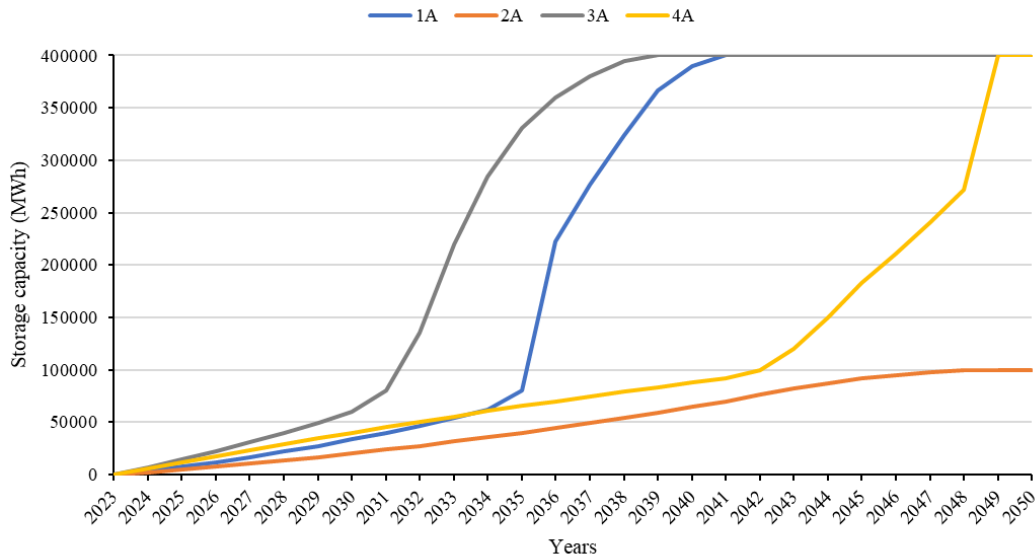


Figure 111 - Optimal storage capacity through the years for the different scenarios

It is essential to highlight that scenarios 1A and 3A, representing low-growth consumption scenarios, follow a similar curve with a temporal lag. Both scenarios show a gradual increase in optimal installed storage capacity values until reaching the limit of 400 GWh. However, in scenario 1A, the increase in storage capacity is not as immediate as in scenario 3A. Specifically, scenario 1A reaches the limit of 400 GWh around 2041, whereas in scenario 3A, this limit is reached around 2038. This outcome aligns with expectations and can be attributed to the accelerated growth in installed power of non-conventional generation sources observed in scenario 3A. This growth promotes the occurrence of more significant generation surpluses during specific periods, which may be stored for later use.

In the high-consumption scenarios (scenarios 2A and 4A), the curves are also similar up to around 2042, with similar conclusions regarding the lagged temporal scale. Scenario 2A is characterized by a high increase in consumption and a conservative increase in non-conventional generation, which justifies that the limit for the storage capacity to be installed equals only 100 GWh. The combination of forecasted evolution for generation capacity and consumption leads to a lower necessity for storage capacity (from the viewpoint of avoided emissions). On the other hand, in scenario 4A, the significant increase in non-conventional generation results in a higher likelihood of generation surpluses, justifying the need to install additional storage capacity. However, it is worth noting that compared to scenario 3A, the threshold of 400 GWh for installed storage capacity is only reached more than a decade later,

specifically in 2049. This situation is due to the influence of the evolution of consumption, which is faster in scenario 4A, delaying the need to install storage capacity.

5.7.3. Influence of load profiles

As mentioned earlier, electric mobility, more specifically the way the batteries of EVs will be charged, may significantly impact the network load profile and, consequently, the amount of emissions that can be avoided. Therefore, this issue is studied in this section by considering the variant scenarios B and C defined in section 5.2.4.2.

5.7.3.1. System without storage

Figure 112 visually compares the annual avoided emissions across various scenarios and their respective variants, as defined in section 5.2.4.3 (Table 21). Therefore, this figure presents the evolution of avoided emissions over time in each scenario, allowing an understanding of electric mobility’s influence on avoided emissions. As observed, the range of expected avoided emissions is constrained by the curves for scenario 1B at the lower end and scenario 4A at the higher end. Over time, the disparity between these limits gradually widens, starting from 3.4 to 3.6 MtonCO₂ in 2023 and escalating to 8.4 to 12.9 MtonCO₂ by 2050.

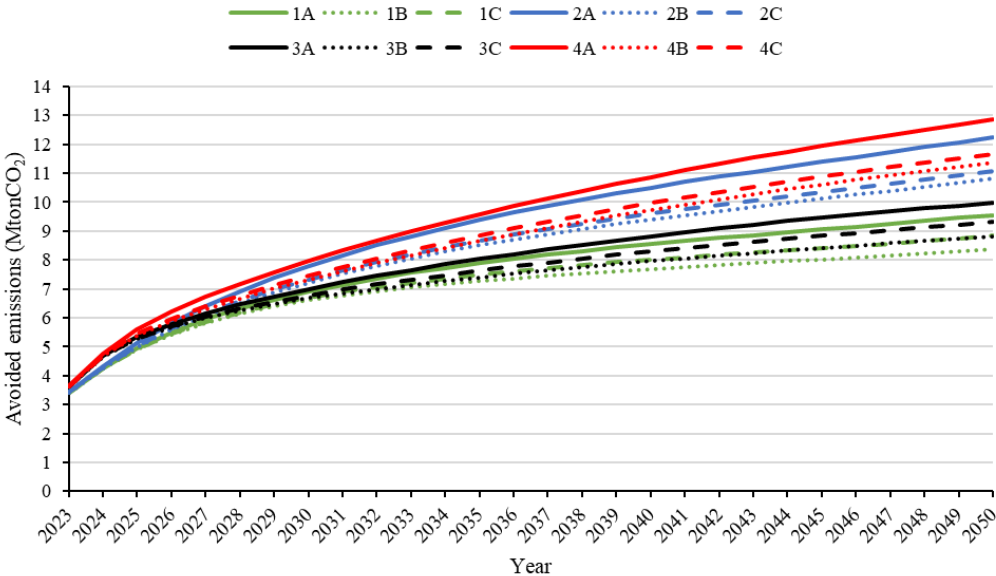


Figure 112 - Influence of EV charging strategy on avoided emissions – system without storage

The findings presented in Figure 112 show that the potential shift in load profile due to EV charging patterns negatively impacts the expected values of avoided emissions. Indeed, the expected values of avoided emissions decrease when consumption profiles B (off-peak charging pattern for EV) and C (blind charging pattern of EV) are assumed. Moreover, the worst result is always obtained for the case of consumption profile B.

The negative impact on avoided losses primarily stems from the deviation of electricity consumption for EV charging from day to night hours in consumption profiles B and C. As a result, less electricity is consumed from non-conventional sources such as PV-based electricity. It is essential to highlight that PV electricity plays a significant role in overall power generation, and no storage systems are being considered.

Figure 113 illustrates the percentual difference in avoided emissions between consumption profiles B and C compared to consumption profile A.

The results indicate similarities between scenarios 1 and 3 and between scenarios 2 and 4. However, it is crucial to highlight that differences become more significant when studying scenarios with higher increases in electricity consumption, namely scenarios 2 and 4. This divergence is particularly evident in the early years of consumption profile B and consistently apparent in the case of consumption profile C. This is because a higher increase in electricity consumption leads to a shift in the consumption pattern, particularly during nighttime hours due to EV charging. As a result, disparities arise between the scenarios.

Therefore, as previously stated, consumption profile B is the one that more negatively impacts the value of avoided emissions. In 2040, for scenarios 1 and 3, the reduction in emissions is approximately 10% lower for consumption profile B and 6% lower for consumption profile C compared to the base load profile (A). However, by 2050, this difference will further increase to -12 % and approximately -7 % for consumption profiles B and C, respectively. Regarding scenarios 2 and 4, a similar difference is observed. By 2040, consumption profile B will experience a reduction of approximately 10%, while consumption profile C shows a decrease of around 8.5%. By 2050, these differences become more pronounced, with consumption profile B decreasing by approximately 12% and consumption profile C decreasing by around 9.5%.

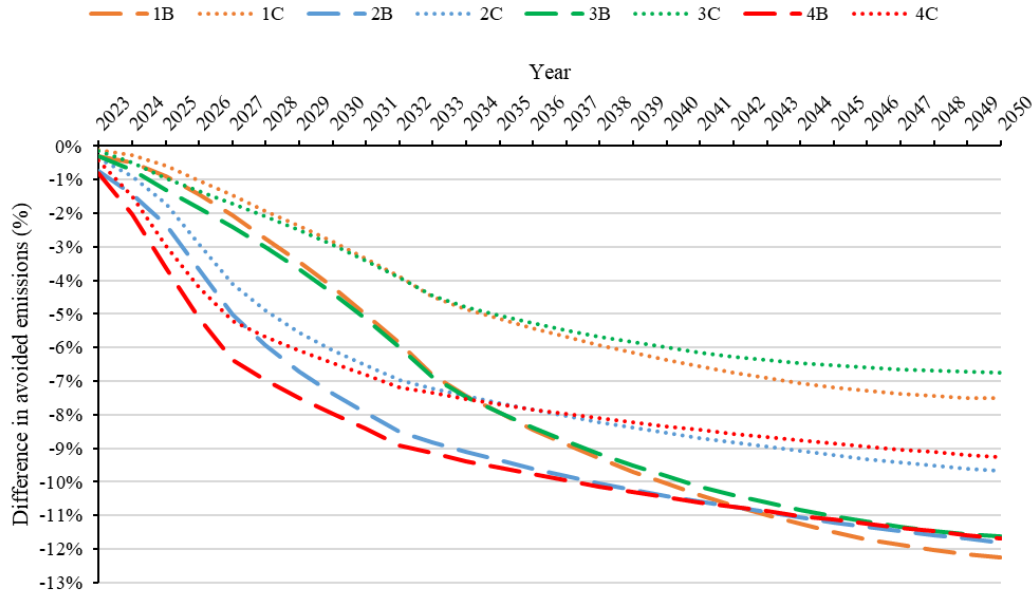
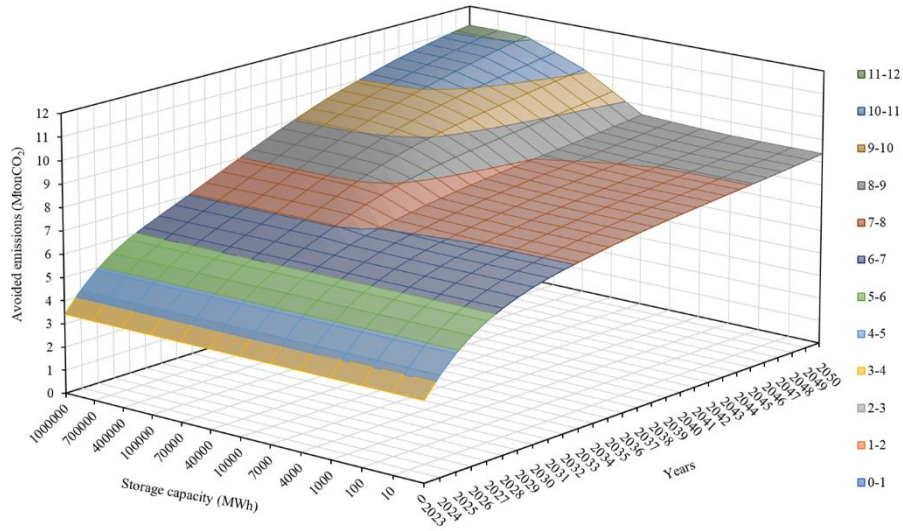


Figure 113 - Percentual difference in avoided emissions – consumption profiles B and C compared to consumption profile A

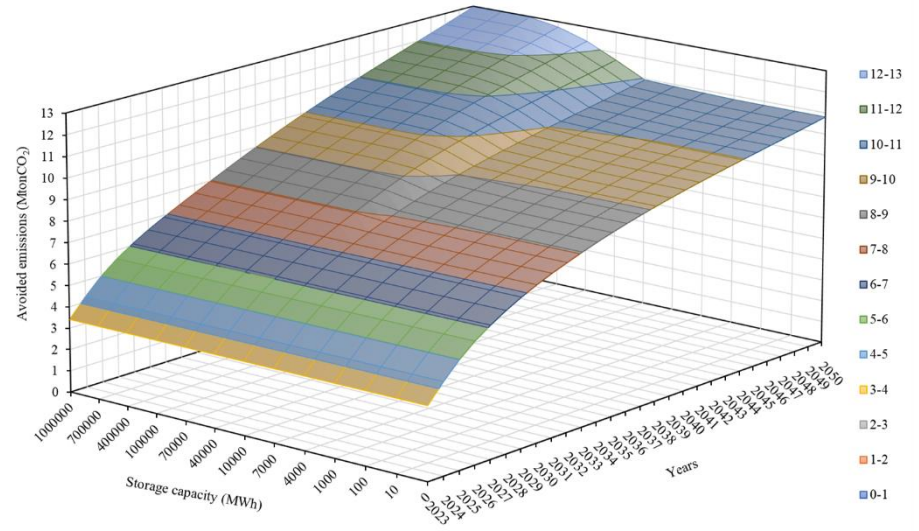
5.7.3.2. System with storage

The assessment of the impact of energy storage on avoided emissions for the cases of consumption profiles B and C implied additional simulations. Therefore, new assessments were conducted to analyze the results accurately. It should be noted that the graphs presented in section 5.7.2 solely represent the base consumption profile (A) case and do not depict the scenarios for consumption profiles B and C.

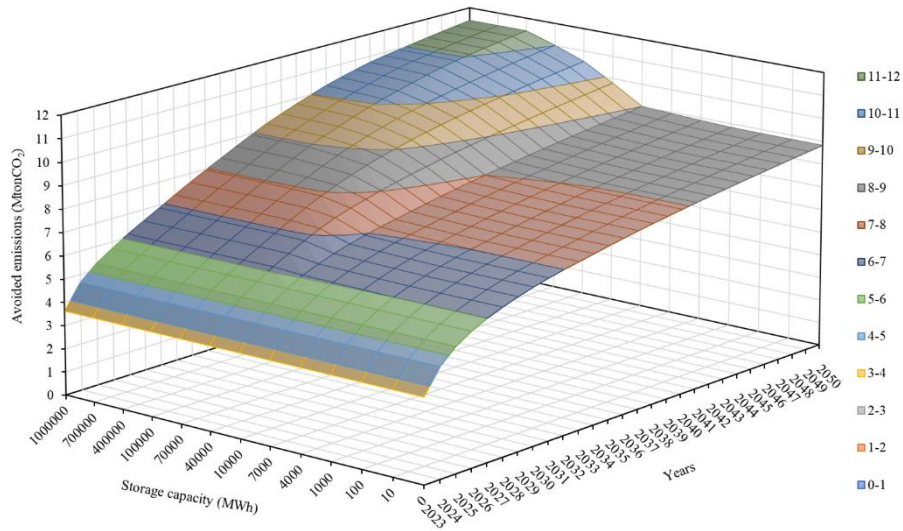
Figure 114 and Figure 115 show the results obtained in the simulations for scenarios 1B to 4B and 1C to 4C, respectively. Some insightful conclusions can be extracted by comparing these results to those presented in Figure 106.



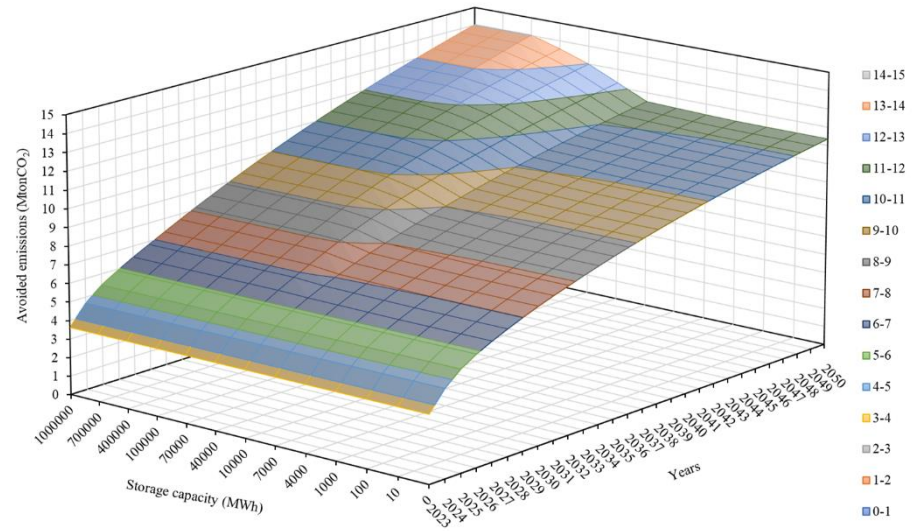
Results of avoided emissions for scenario 1B



Results of avoided emissions for scenario 2B

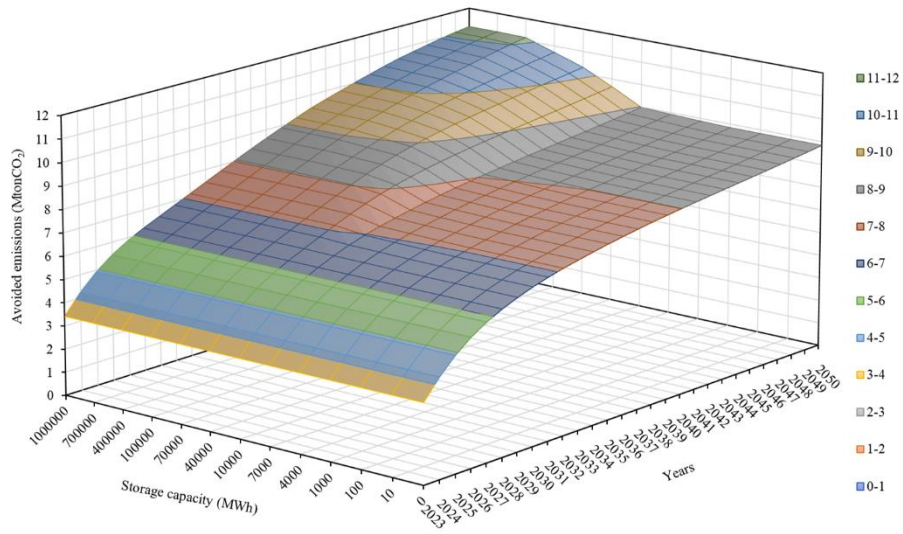


Results of avoided emissions for scenario 3B

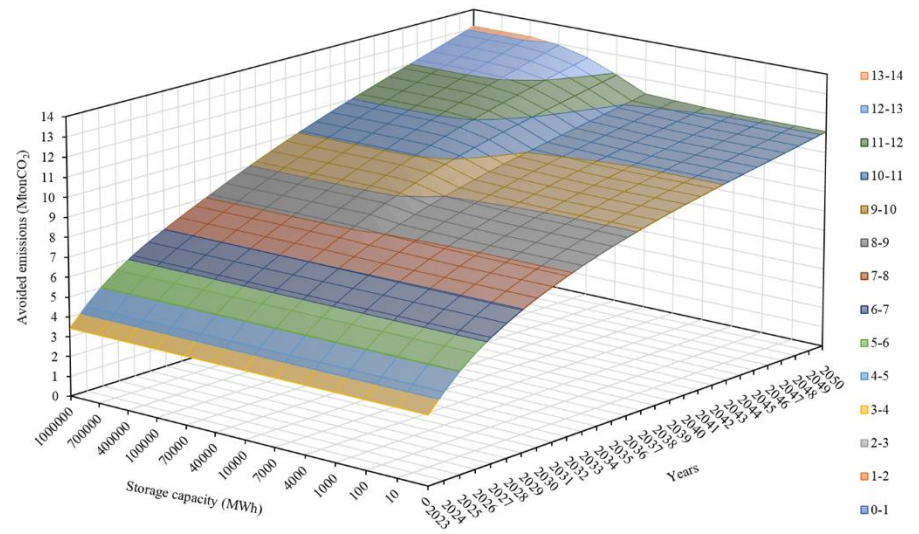


Results of avoided emissions for scenario 4B

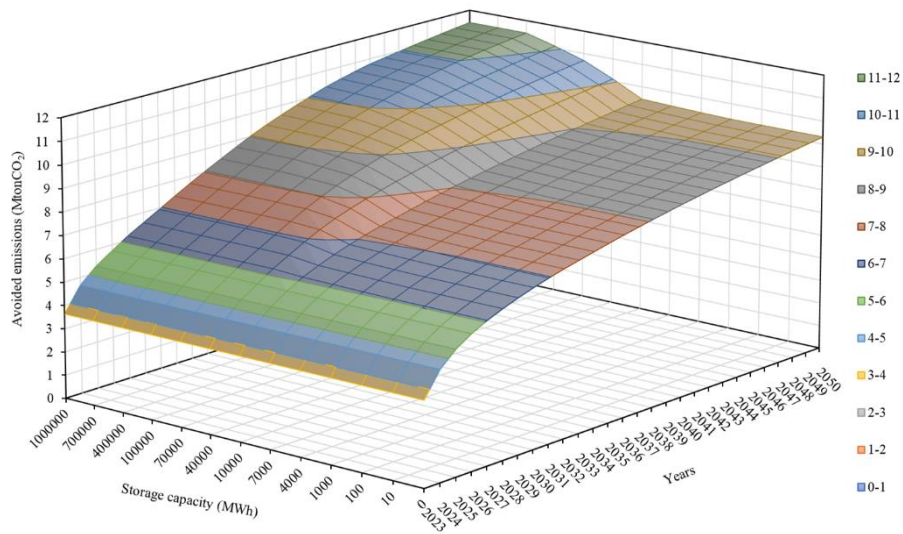
Figure 114 - Results of avoided emissions for scenarios 1B, 2B, 3B and 4B



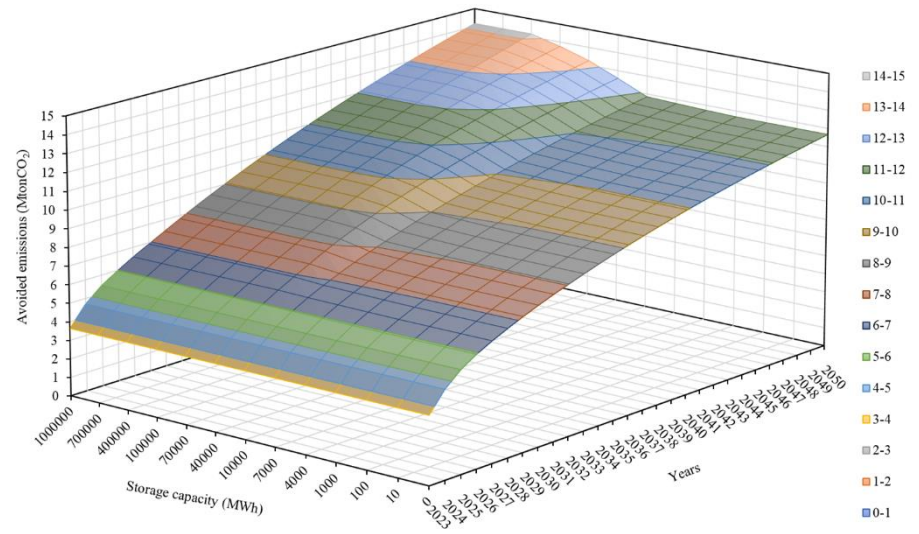
Results of avoided emissions for scenario 1C



Results of avoided emissions for scenario 2C



Results of avoided emissions for scenario 3C



Results of avoided emissions for scenario 4C

Figure 115 - Results of avoided emissions for scenarios 1C, 2C, 3C and 4C

The results show that the impact of storage systems is negligible for installed capacities up to 10 GWh, which is comparable to the base load scenario. Additionally, regardless of the scenarios considered, the 400 GWh capacity emerges as the threshold where the potential for emissions reduction plateaus. This value is also applied to scenario 2, a significant difference in the base consumption profile. Indeed, the capacity that previously yielded no further emissions reduction when the base consumption profile was 100 GWh.

When the considered storage capacity surpasses the threshold at which additional gains cease (400 GWh), the absolute values of avoided emissions exhibit insignificant differences compared to the base case scenarios (scenarios 1A, 2A, 3A, and 4A, as mentioned in section 5.7.2). Particularly, the variances are minor in scenarios characterized by a low increase in demand (scenarios 1 and 3). For instance, both scenarios 1B and 1C reach avoided emissions of 11.1 MtonCO₂ in 2050, just 0.1 MtonCO₂ less than in scenario 1A. In scenarios 3B and 3C, the difference is even less pronounced compared to scenario 3A. Notably, scenarios characterized by a high increase in consumption (scenarios 2 and 4) show a more substantial difference. In the case of scenario 2B by 2050, the potential reaches 13 MtonCO₂, whereas for scenario 2C, it reaches 13.1 MtonCO₂. This represents a decrease of 0.4 MtonCO₂ and 0.3 MtonCO₂ respectively compared to the base scenario 2A. In scenarios 4B and 4C, the potential for emission reduction is projected to be 14 MtonCO₂ and 14.1 MtonCO₂ respectively by 2050. This indicates a modest decrease of 0.5 and 0.4 MtonCO₂ compared to scenario 4A. It is worth mentioning that these differences represent less than a 3.6% reduction in the potential of preventing emissions when compared to the base case scenarios.

As observed in the preceding section (section 5.7.3.1), the most notable impact that the potential load profile change resulting from electric vehicles (EVs) can have is when storage is not considered. This situation emphasizes the significance of incorporating storage systems in such scenarios, resulting in a more substantial disparity in the potential for emissions avoidance between scenarios with and without storage consideration. For instance, the percentual difference between having 400 GWh of storage capacity and not considering storage, compared to the findings obtained in the base cases outlined in section 5.7.2, is substantially larger. In scenario 1B, this difference reaches 32.4%, while in scenario 1C, it stands at 26%, contrasting with the 17.1% observed in scenario 1A. In scenario 2B, the difference extends to 20%; in scenario 2C, it reaches 18.5%, as opposed to the 10% noted in scenario 2A. For scenario 3B, the difference is notable at 29.6%, and in scenario 3C, it is up to 22.9%, bearing in mind that scenario 3A recorded a difference of 14.6%. In scenario 4B, the difference now climbs to

23.5%, and for scenario 4C, it reaches 21.3%, while scenario 4A demonstrated a difference of 12.4%.

The load profile change due to the effect of EV charging also has implications regarding the moments for installing storage capacity. Figure 116 demonstrates a substantial acceleration in the growth of the optimal value of accumulated installed capacity over time when comparing consumption profile B to the base consumption profile A. Regarding load profile C, the outcome is slightly different. The accumulated optimal storage capacity follows a very similar behaviour to consumption profile A until the value of 70 GWh is achieved. Then, the optimal installed capacity for the case of consumption profile C appears delayed by around 3 years until a value of around 120 GWh is achieved. After this capacity value, the accumulated capacity for the case of consumption profile C accelerates significantly.

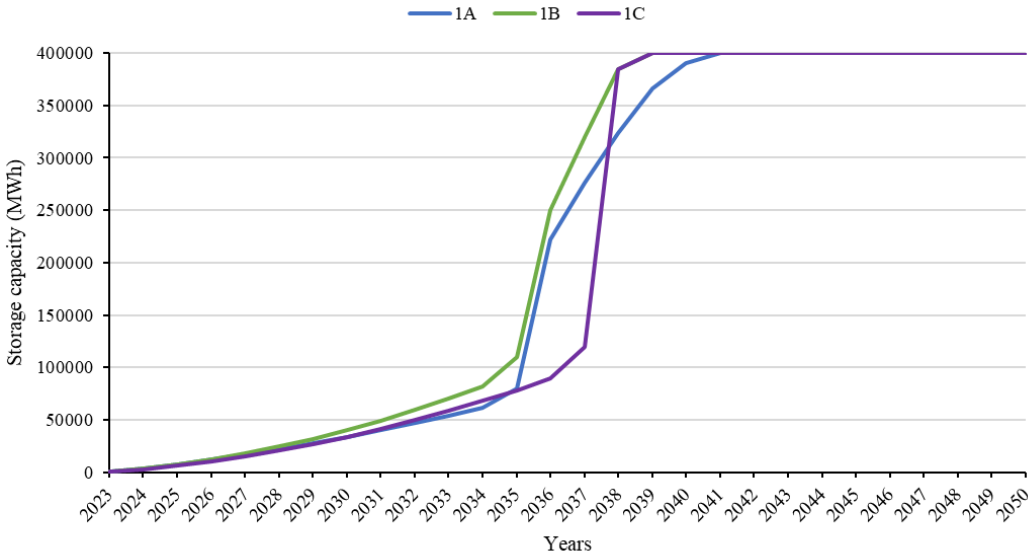


Figure 116 - Optimal storage capacity over the years for scenarios 1A, 1B and 1C

5.7.4. Influence of the generation distribution across the networks

Decentralization of electricity generation involves placing relatively small power plants closer to the consumption points. Decentralization offers various advantages, including increased flexibility, reliability, and environmental benefits [143]. Moreover, decentralization using microgrids and optimization procedures can also result in avoided emissions, as demonstrated in [144].

The reduction in emissions due to non-conventional generation is due, firstly, to the fact that these plants use renewable resources as primary energy, thus replacing fossil-based production. However, as explained in Chapter 4, the avoided emissions are also influenced by the avoided losses in transmission and distribution networks. Therefore, the placement of non-conventional power generation along electrical networks can significantly impact the resulting reduction of emissions. When the generation sources are situated close to consumption areas, the value of avoided emissions tends to increase. However, an excessive concentration of generation in specific networks can lead to the reversal of power flows, ultimately reducing the value of emissions reduction.

Therefore, this section shows a sensitivity analysis of avoided emissions as a function of the placement of non-conventional generation. The analysis considered only the installed capacity in photovoltaic generators, which are more likely to be connected to any network in the electrical system due to their modularity.

This analysis will consider the base scenarios (1A, 2A, 3A and 4A). Additionally, we will assume a gradual rise in the penetration of PV generation capacity at LV and MV networks, as depicted in Figure 117.

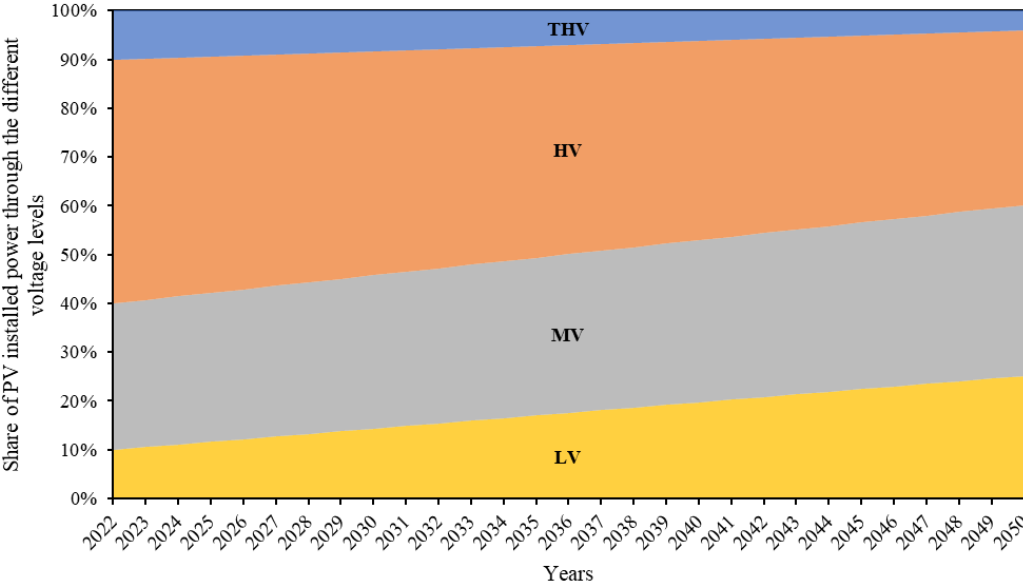


Figure 117 - Adopted proportion of installed PV power across the networks

It is worth mentioning that while the proportion of PV installed capacity at HV and THV levels has decreased, this does not mean there has been a decrease in overall installed capacity. The capacity at these higher voltage levels is still increasing, albeit slower than the lower voltage levels, as shown in Figure 118.

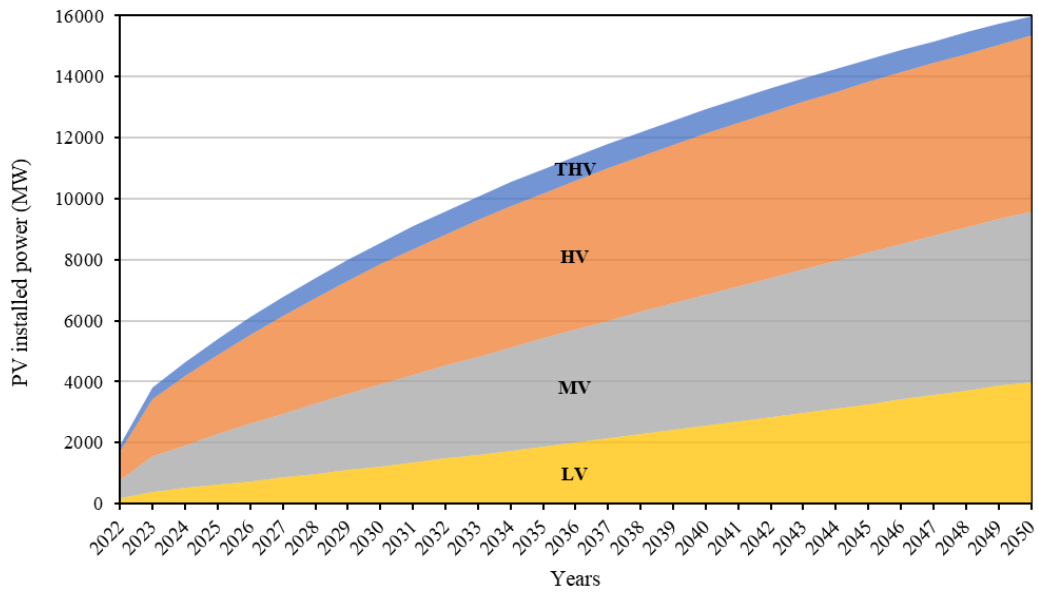
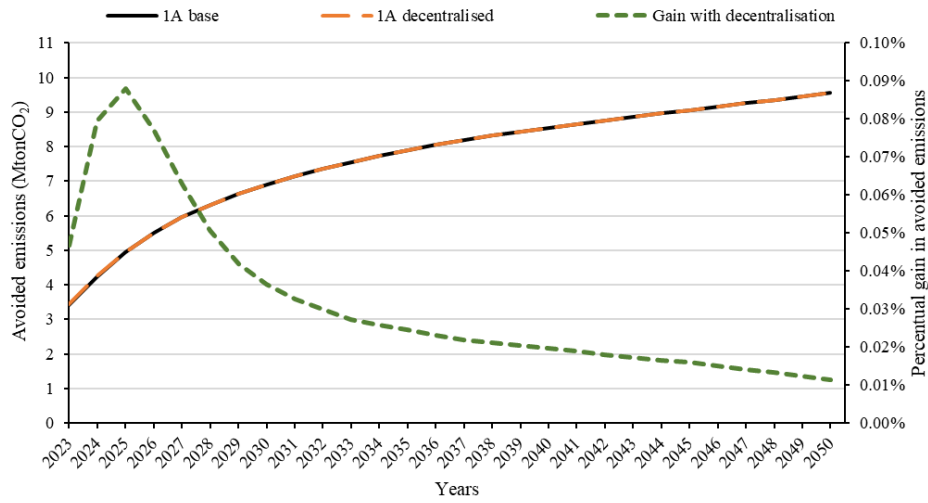
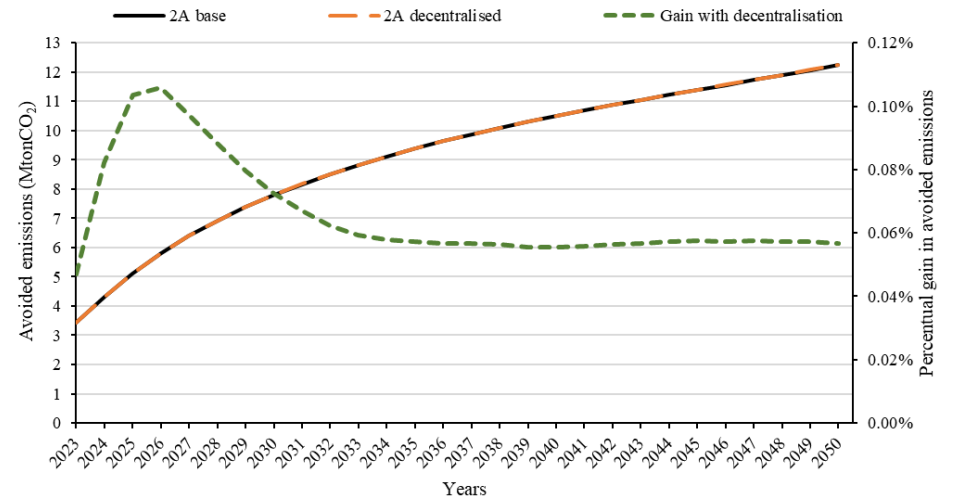


Figure 118 - Evolution of installed PV power across the networks

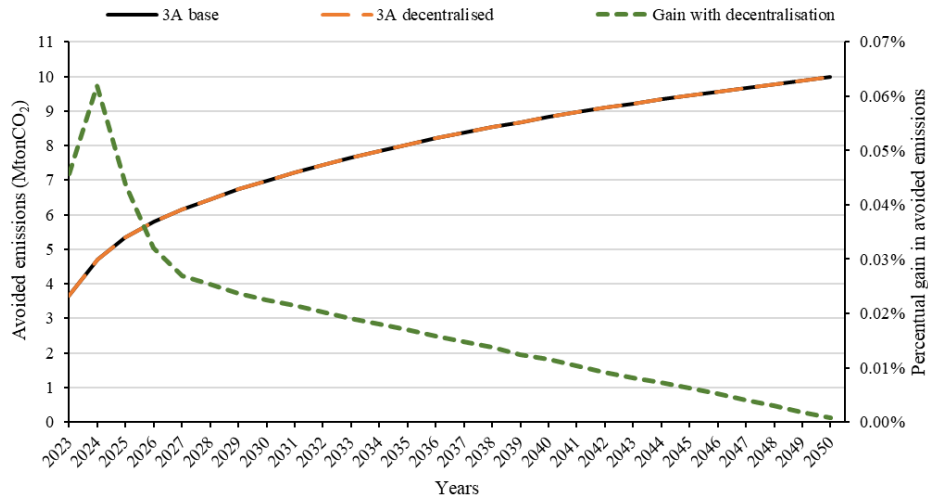
Figure 119 shows the evolution of avoided emissions when storage is not considered. Note that the curve in black represents the base situation where the proportion of PV installed capacity equals the one established in section 5.3.2. The orange line shows the forecasted avoided losses when the proportion of PV installed capacity assumes the values presented in Figure 117.



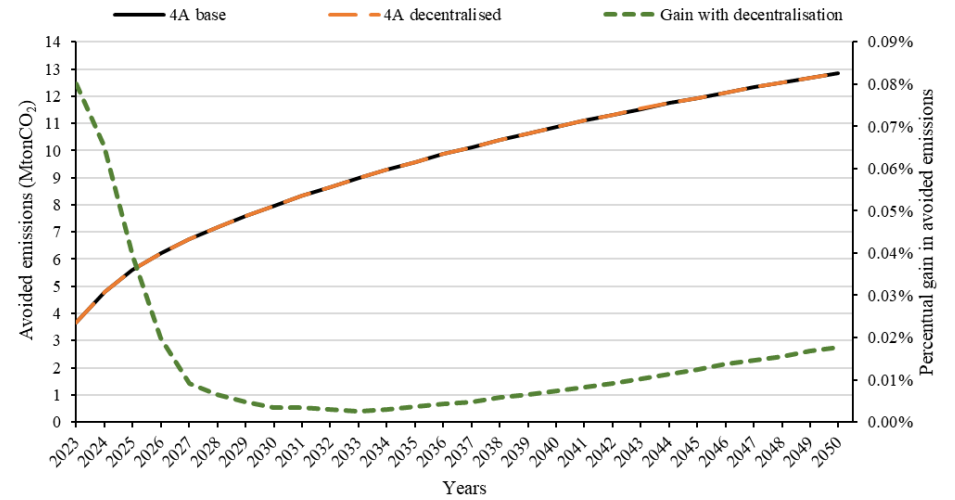
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A

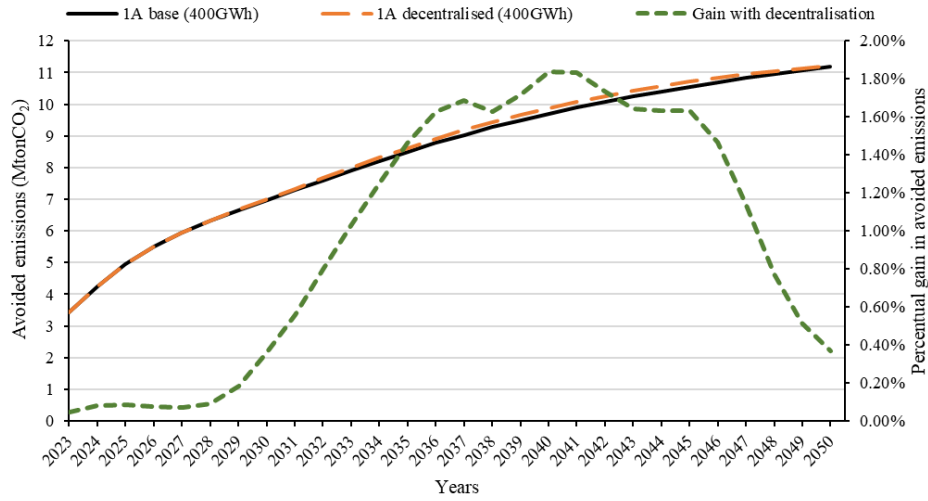


Results for scenario 4A

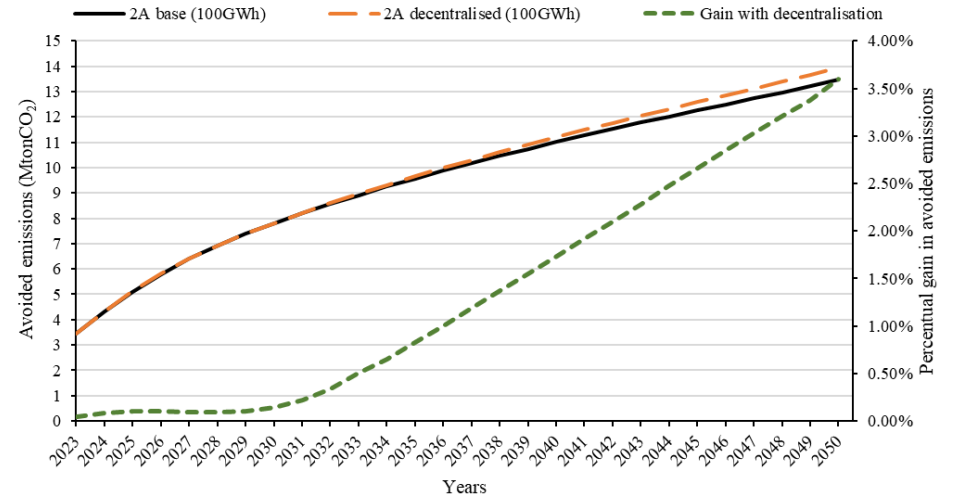
Figure 119 - Avoided emissions gain due to higher concentration of PV generation in a system without storage

The minimal impact on avoided emissions becomes apparent when observing the results, indicating that the higher concentration of photovoltaic generation in LV and MV networks barely affects emissions reduction. It is essential to highlight that the emissions avoided by replacing generation based on fossil fuels (natural gas, in this case) by PV generation do not depend on the location of the PV generators, namely when no energy storage exists. Therefore, in this case, the impact is fundamentally due to reduced electricity transmission and distribution losses, which tend to be more significant when production approaches the load. Thus, the potential of higher installed PV capacity at LV and MV networks only depends on the avoided losses in the upstream networks. Moreover, the lost energy can, in turn, be generated (totally or partially) using generators with reduced emissions, which helps to make the increase in avoided emissions less significant.

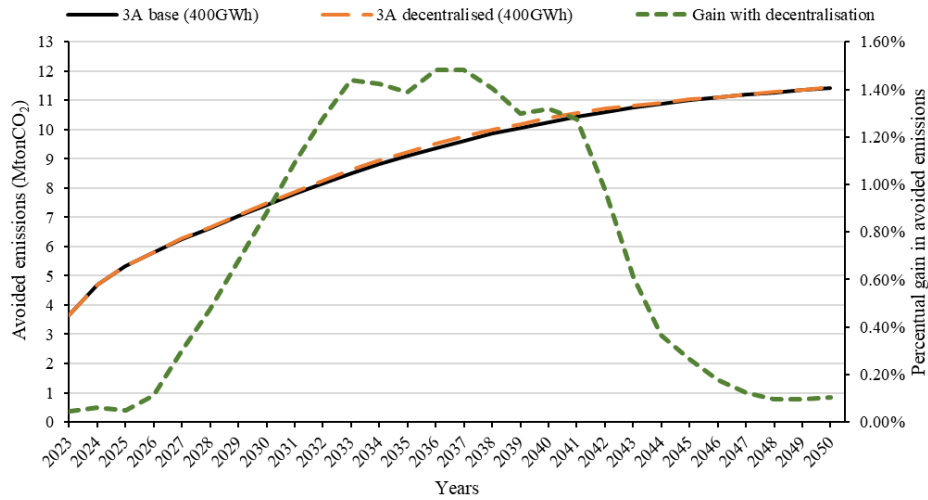
The situation explained previously can be altered with the introduction of storage systems. Storage facilitates the decoupling of electricity generation and consumption, resulting in a more significant reduction in emissions. This reduction is particularly evident when stored energy is consumed during periods characterized by more intensive use of fossil fuel power plants. The results depicted in Figure 120 demonstrate the positive impact on avoided emissions resulting from a higher concentration of PV generators on LV and MV networks when 400 GWh of storage capacity exists. The distribution of storage capacity assumed in the simulation is referred to in section 5.6. Note that the increasing percentual gain in avoided emissions is due to the steady growth in the installed capacity of PV generation over the years. In the early years, the gains were limited due to the smaller installed capacity of non-conventional generation and the consequent lower value of surplus generation to be stored for later consumption.



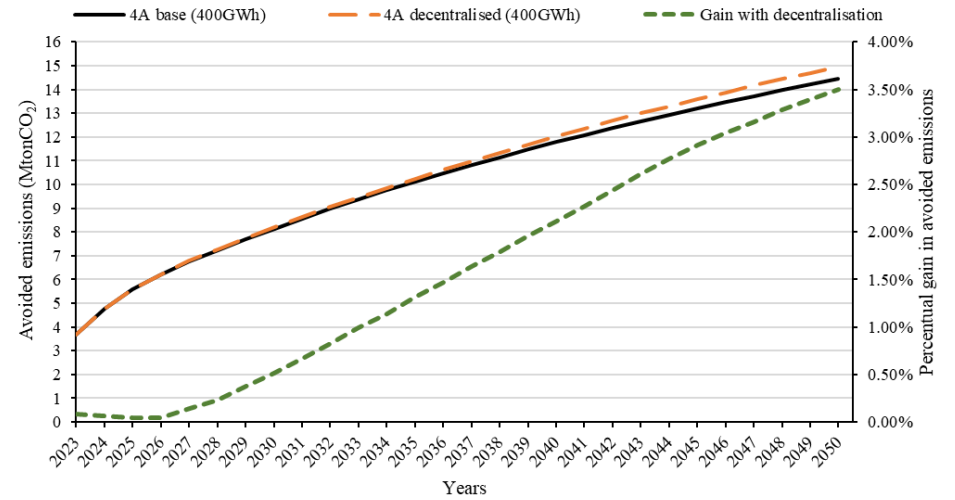
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A



Results for scenario 4A

Figure 120 - Avoided emissions gain due to higher concentration of PV generation in a system with storage

The information in Figure 120 shows that the potential of storage systems associated with a higher concentration of PV systems in LV and MV networks tends to enhance avoided emissions. Therefore, it is possible to infer that storage systems may have a complementary role in maximizing the environmental benefits of decentralization efforts.

The decline in gains observed with decentralization (green curve) in scenarios characterized by a low increase in demand (scenarios 1A and 3A) can be attributed to the reasons mentioned earlier. There is a significant decrease after a specific year in these cases because the demand remains relatively low while the energy generation rate increases rapidly. As a result, the storage systems become saturated, leading to surpluses.

5.7.5. Influence of the storage systems distribution across the networks

As in the case of generators, the greater or lesser concentration of storage systems can also influence the value of avoided emissions. Therefore, in this section, an assessment is made of the potential impact produced by how storage capacity is distributed along electrical networks.

The method employed in this study involved two cases: one where the storage systems are allocated based on the energy generation pattern (Case 1) and the other where the storage systems are distributed according to the energy consumption pattern (Case 2). The consumption pattern corresponds to the one presented in section 5.3.1. The generation pattern was determined by considering the expected energy generation in each network level in each year of the study period, excluding the natural gas-based generation. Those generation values depend on the installed capacity of non-conventional generation throughout the study period and the generation profile of each generation’s technology (explained in section 5.2.1). Therefore, the generation pattern is dynamic, varying over the years.

Table 28 shows the adopted distributions and the base distribution defined in section 5.6 (Base Case). Note that for Case 1, three sets of values are presented.

Table 28 - Adopted Storage distribution for the different cases

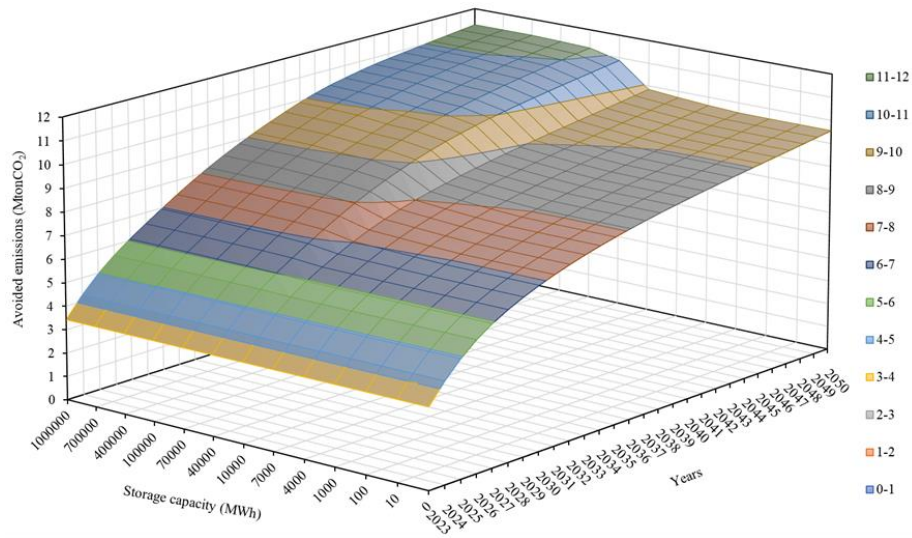
		VHV	THV	HV	MV	LV
Case 1	2023	6%	26%	59%	7%	2%
	2040	3%	17%	63%	13%	4%
	2050	3%	16%	64%	13%	4%
Case 2		-	5%	15%	30%	50%
Base case		-	-	40%	30%	30%

Figure 121 illustrates the results for the case where the storage systems are distributed according to the generation pattern. Note that the base scenarios (1A, 2A, 3A and 4A) were adopted for the simulations.

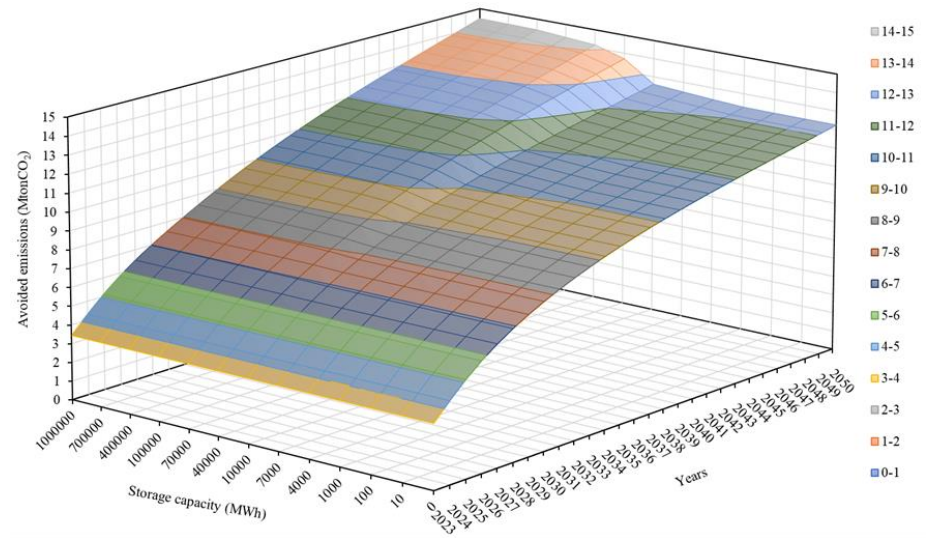
The outcomes depicted in Figure 121 can be compared with those in Figure 106. It is important to note that the outcome in Figure 106 corresponds to the storage capacity distributed according to the Base Case, as outlined in Table 27 of section 5.6. The comparative analysis indicates that, in Case 1, the optimal potential for mitigating emissions is attained with a mere 70 GWh storage capacity for each scenario. In contrast, the Base Case reaches its highest potential only when 400 GWh of storage capacity is implemented for scenarios 1A, 3A, and 4A, whereas scenario 2A involves 100 GWh.

Note that in scenarios with high consumption growth, there is still potential for avoided emissions with over 70 GWh of storage capacity. However, beyond that threshold, the most notable gain is merely 2% for scenario 2A and 2.3% for scenario 4A in 2050, considering a storage capacity of 400 GWh instead of 70 GWh.

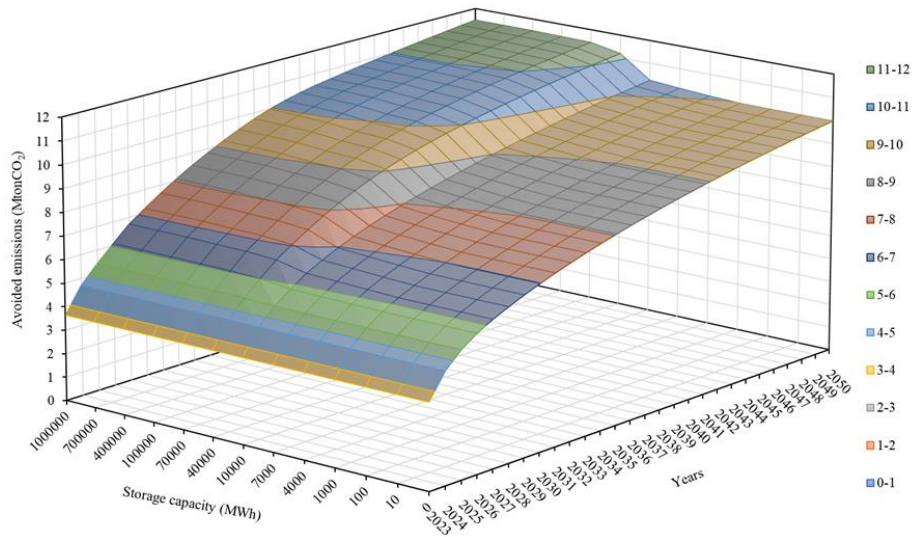
Now, let us explore what happens when storage systems are distributed according to the consumption pattern. Figure 122 provides the results for this situation (Case 2). Once again, a significant difference is observed. However, in this situation, the highest potential of avoided emissions is achieved for a storage capacity of 400 GWh. The major difference happens with capacities between 10 GWh and 400 GWh, where the potential to avoid emission is severely reduced compared to the base scenario in Figure 106.



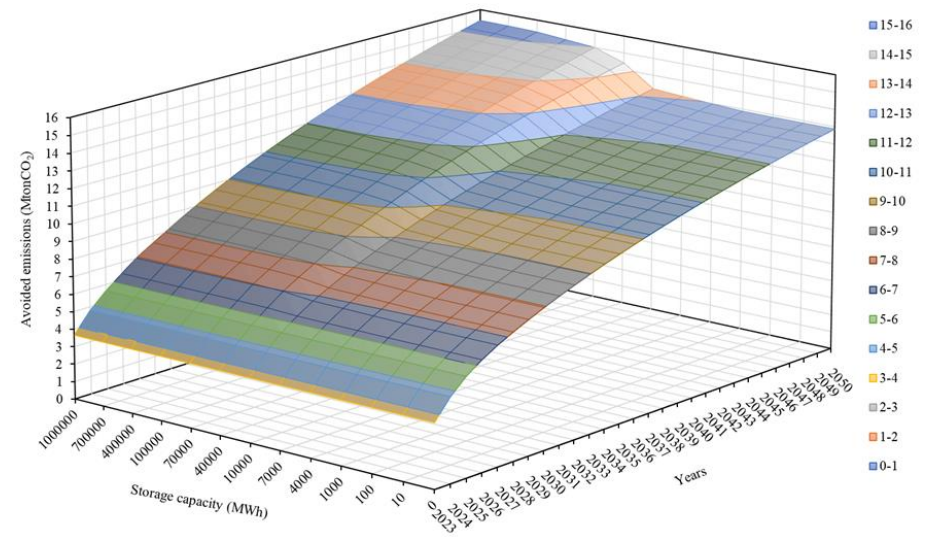
Results for scenario 1A



Results for scenario 2A

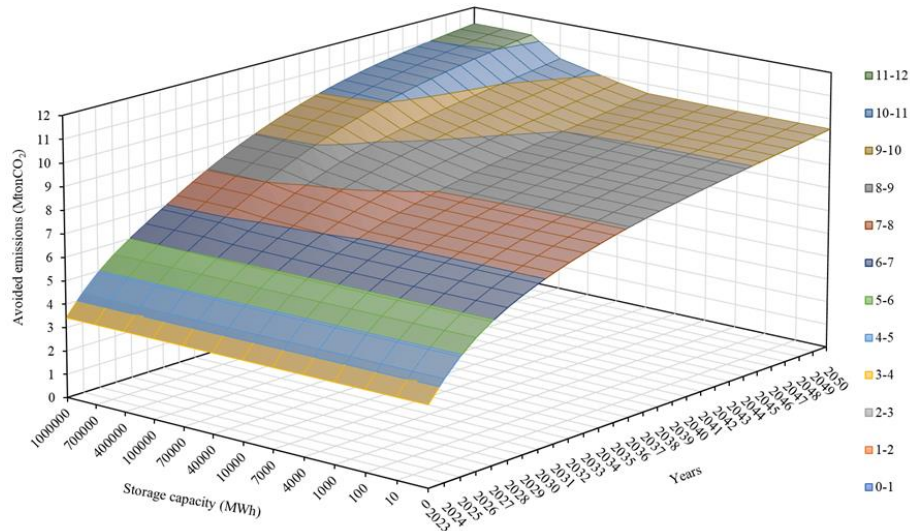


Results for scenario 3A

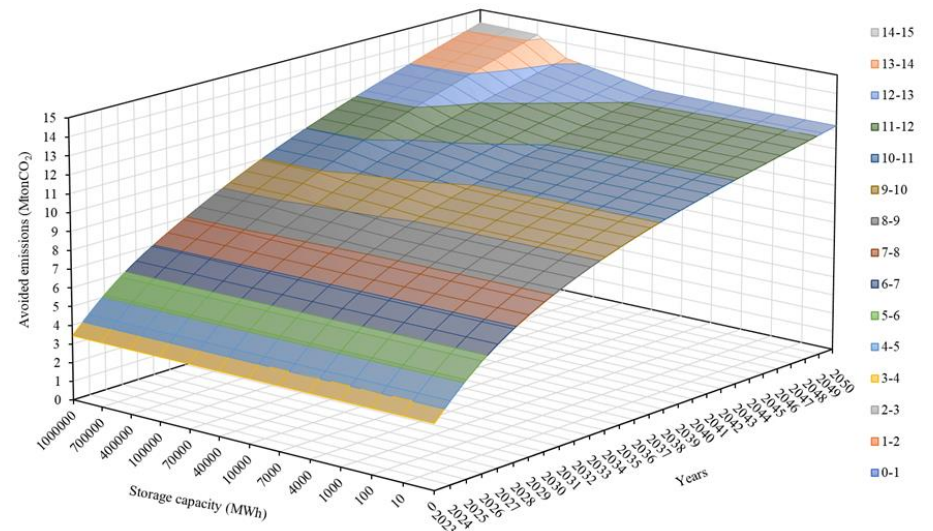


Results for scenario 4A

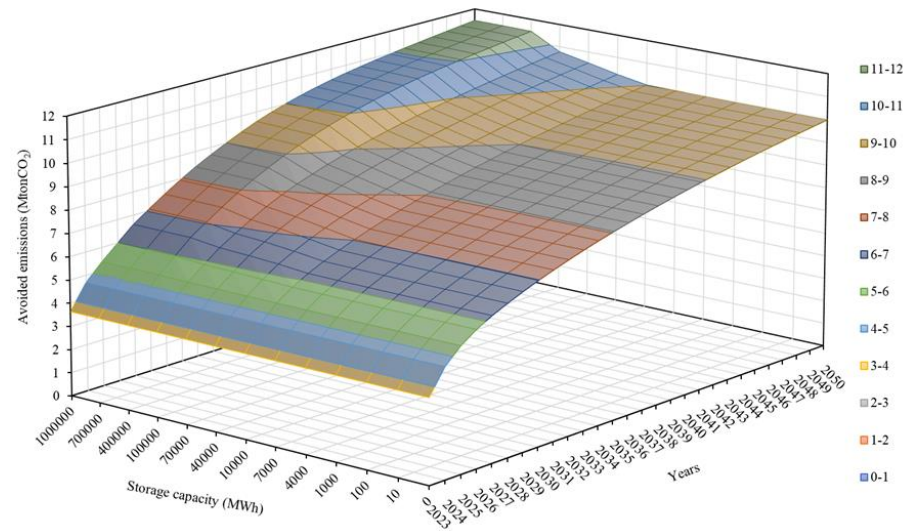
Figure 121 - Impact on avoided emissions due to storage systems distributed according to the pattern of generation



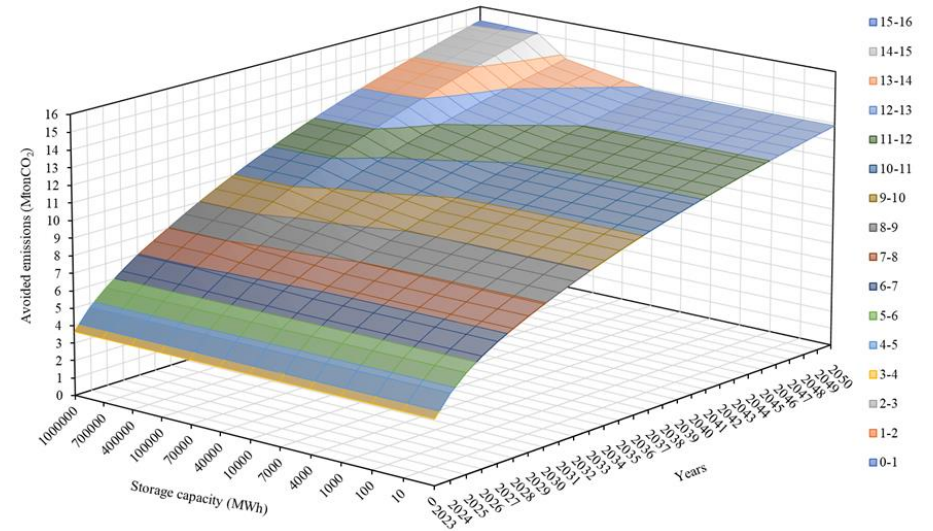
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A

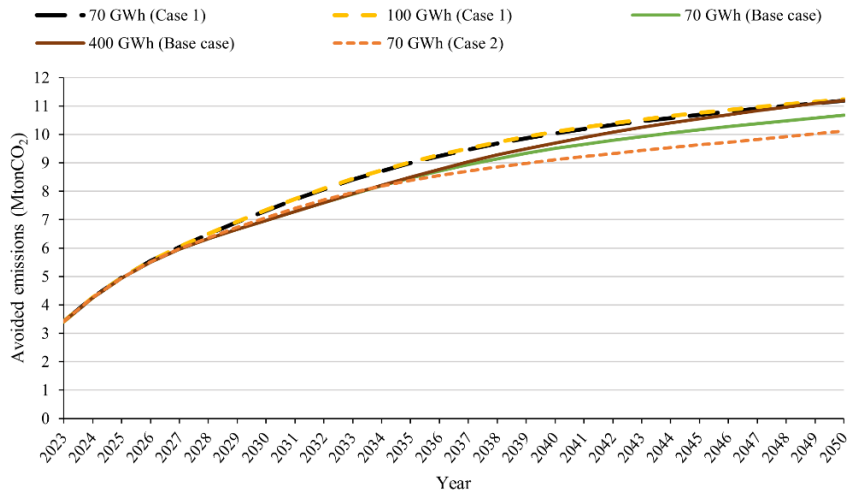


Results for scenario 4A

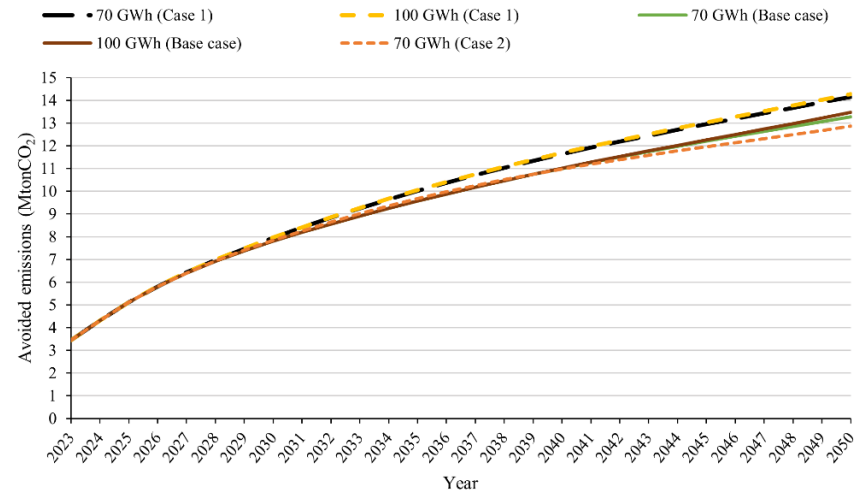
Figure 122 - Impact on avoided emissions due to storage systems distributed according to the pattern of consumption

Figure 123 clarifies how the distribution of storage capacity can impact the value of avoided emissions. It considers the previously highlighted values of 70 GWh, 100 GWh, and 400 GWh. Including the results for 100 GWh of storage capacity in case 1 allows us to compare with the situation regarding a capacity of 70 GWh in the same scenario. By doing this, we can observe that no substantial benefits are gained when exceeding 70 GWh in both scenarios.

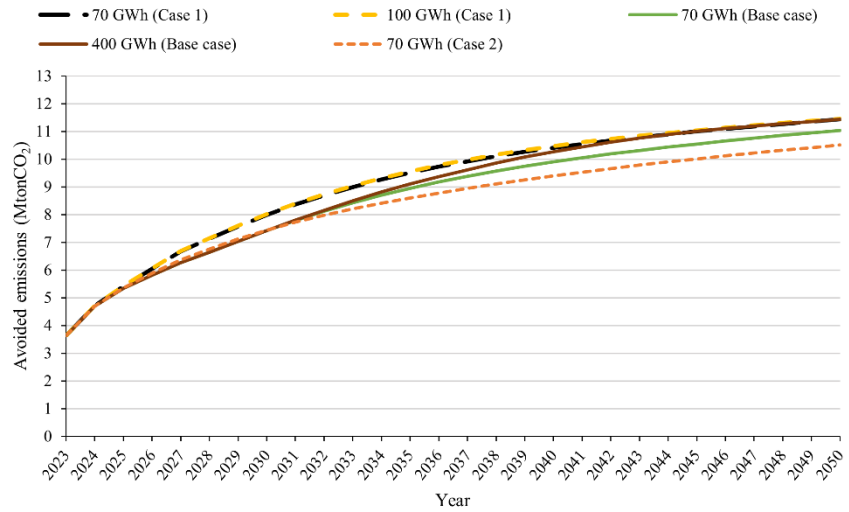
The main conclusion that may be extracted from the results is that the avoided emissions tend to be more relevant when storage systems are located according to the generation pattern. Distributing 70 GWh of storage capacity according to the generation pattern leads to more emissions avoidance than 400 GWh for the high-demand growth scenarios (scenarios 2A and 4A). In the other two scenarios (scenarios 1A and 3A), 70 GWh of storage capacity can also lead to more emission avoidance than 400 GWh in the early years. It tends to achieve the same results as the base scenario in the latter years.



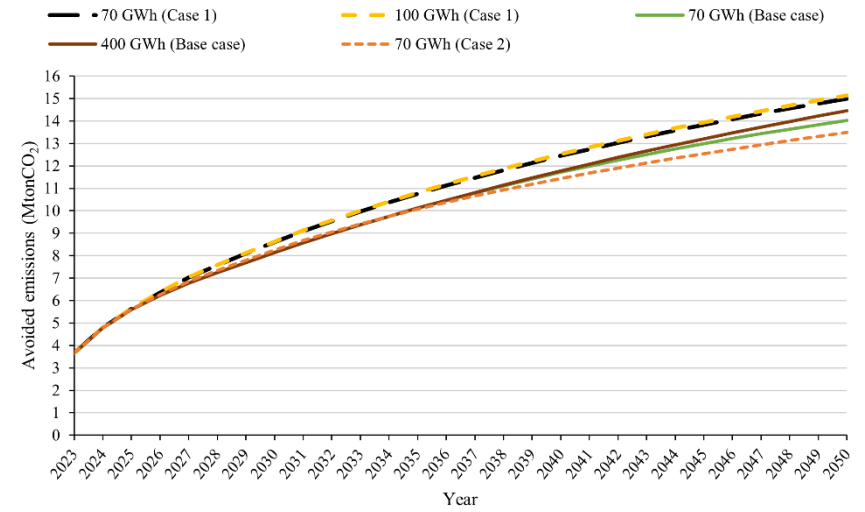
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A



Results for scenario 4A

Figure 123 - Comparison between different distribution patterns of storage systems

As observed, the distribution of storage capacity according to the consumption pattern reveals worse results regarding avoided emissions. The assumptions discussed in Chapter 4, namely the belief that energy surpluses are only stored in the same network where they occur, may justify this conclusion. Indeed, this assumption can significantly contribute to overlooking a portion of surplus energy that arises in specific periods, mainly when there is insufficient storage capacity, thus disregarding its impact on accounting for avoided emissions. In simpler terms, when there is more installed storage capacity in networks with lower voltages, generation surpluses are more likely to be wasted if there isn't enough capacity to store it. Therefore, those surpluses wouldn't count towards reducing emissions.

On the other hand, if storage capacity aligns with production patterns, more storage capacity tends to be installed in networks with higher voltages. This fact tends to increase the amount of stored energy over time. Moreover, according to the developed model, the energy stored at higher voltage networks can be used to meet downstream consumption needs. However, according to the model, the stored energy cannot be used to supply upstream networks' consumptions. This issue needs to be more explored in future works.

5.7.6. Indirect emissions of the storage systems

Until now, our discussion about storage systems' contribution to avoiding emissions was focused on their operational phase. However, it's crucial to address another significant aspect, particularly relevant in today's context: the emissions associated with battery manufacturing.

In this study, we have specifically examined electrochemical storage systems, primarily focusing on lithium-ion batteries. These batteries represent the dominant and most competitive technology in energy storage today, making them the most likely choice for widespread adoption.

The emissions linked to battery manufacturing can substantially impact the overall environmental footprint of the energy storage systems. This factor adds another layer of complexity to our analysis, as it necessitates a comprehensive evaluation of emissions across the entire lifecycle of these systems, encompassing both manufacturing and operational phases.

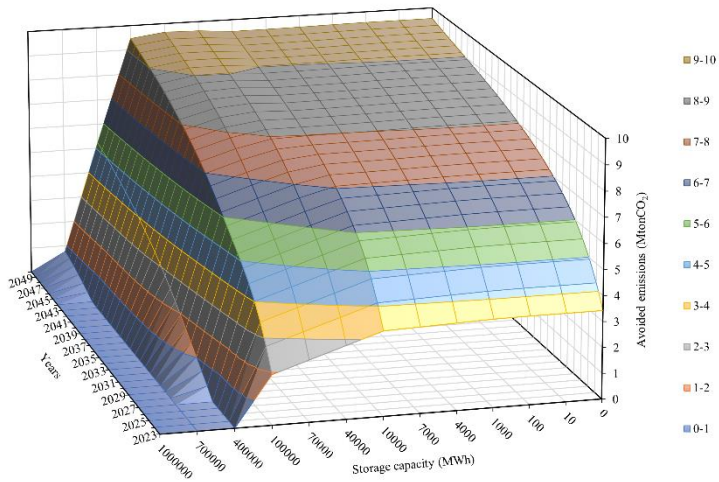
A comprehensive study in [145] thoroughly reviews research on emissions of lithium-ion batteries. This study reveals that emissions linked to the manufacturing of these batteries

can range from 27 to 271 kgCO₂ per kWh of capacity. This considerable variability is attributed to diverse factors, including the source of the raw materials and the location of the manufacturing facility.

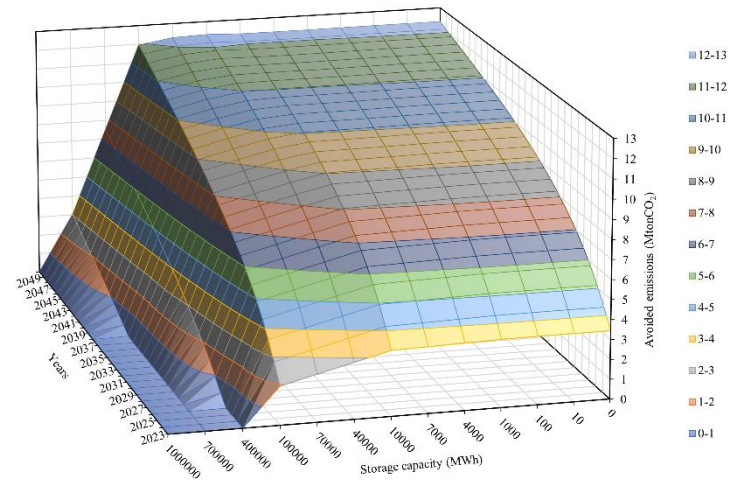
The base scenarios (1A, 2A, 3A, 4A) were adopted in the simulations. Moreover, an initial storage capacity of 100 MWh in 2023 was considered, and a gradual linear increase in this capacity was applied until it reached 400 GWh by the year 2050 for scenarios 1A, 3A and 4A. For scenario 2A, a maximum value of 100 GWh was adopted. This particular capacity limit is selected based on the observation made in section 5.7.2, where it was identified as the threshold that levels off the potential for avoided emissions.

The lifespan of the batteries needs to be included in the analysis. Therefore, a battery lifespan of 10 years was adopted. Thus, the batteries need to be replaced ten years after their installation. Accordingly, the emissions associated with expanding storage capacity and replacing ageing battery systems are accounted for throughout the study.

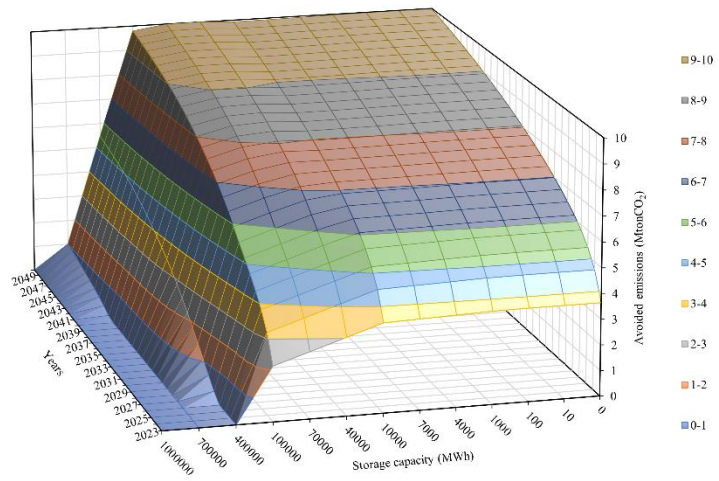
Figure 124 depicts the results when the indirect emissions associated with the storage systems are accounted for. The values of this figure may be compared with the results in Figure 106 (where the indirect emissions of storage systems were not considered). Note that Figure 124 is presented from a different perspective for improved clarity. A 149 kgCO₂/kWh value was adopted for the indirect emissions of storage systems, representing the average value in the literature.



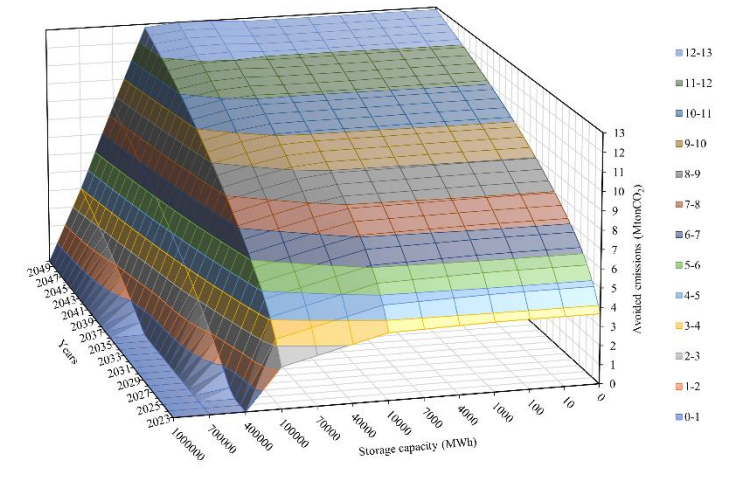
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A



Results for scenario 4A

Figure 124 - Results adjusted for indirect emissions associated with storage systems

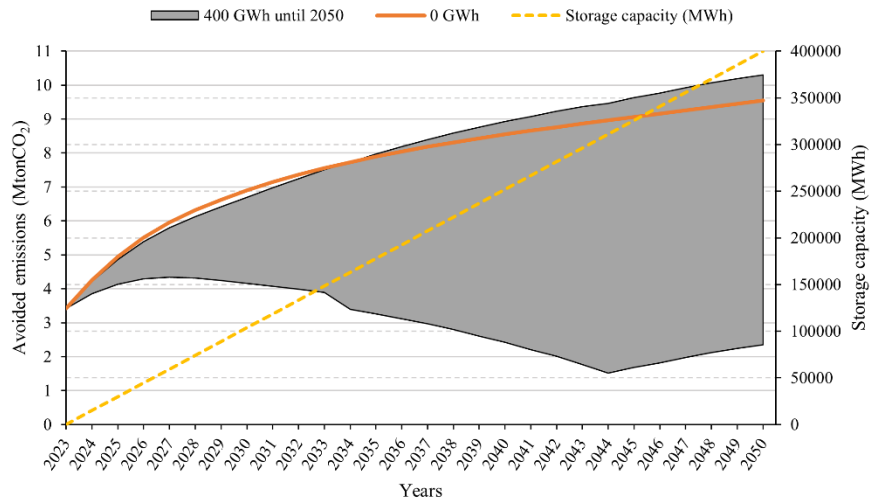
As evident from the results, accounting for indirect emissions undermines the contribution of storage systems for avoided emissions. However, there is still potential for positive effects of storage systems regarding avoided emissions, namely for installed capacity until 100 GWh. Note that the avoided emissions value decreases quickly for capacities higher than 100 GWh.

The influence of the chosen value for indirect emissions may be observed in Figure 125, where the range of 27 to 271 kgCO₂ per kWh was assumed. The grey area on the graph represents the results when the mentioned range is considered.

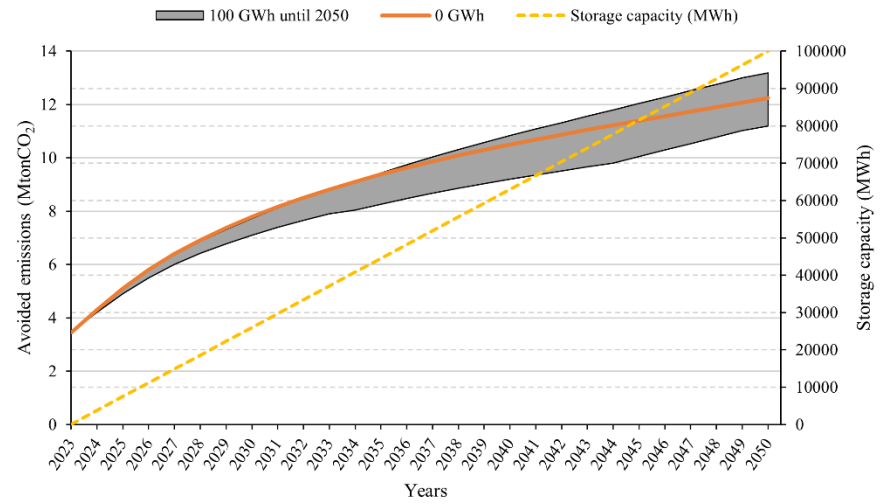
As observed, the emissions related to battery manufacturing can significantly impact the contribution of storage systems to the avoided emissions. The potential for avoiding emissions becomes quite limited in all scenarios, as indicated by the small grey area above the orange line, representing the avoided emissions when no storage systems are assumed. Even at its best, the storage capacity falls short of completely offsetting emissions compared to not considering storage at all.

As seen in the results of Figure 124, when considering the average value of the emission factor, the capacity that maximizes avoided emissions becomes 100 GWh. Figure 126 shows the results for that capacity when the range of the emission factor is considered.

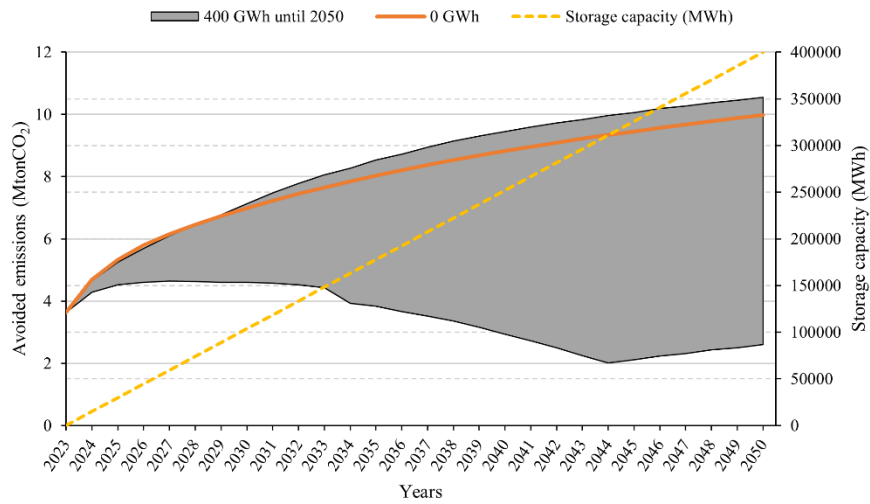
The figure shows more promising results, indicating that incorporating storage in our analysis could have positive impacts. However, it is important to note that if we consider the upper range of the emission factor, the results may still be less favourable compared to not considering storage.



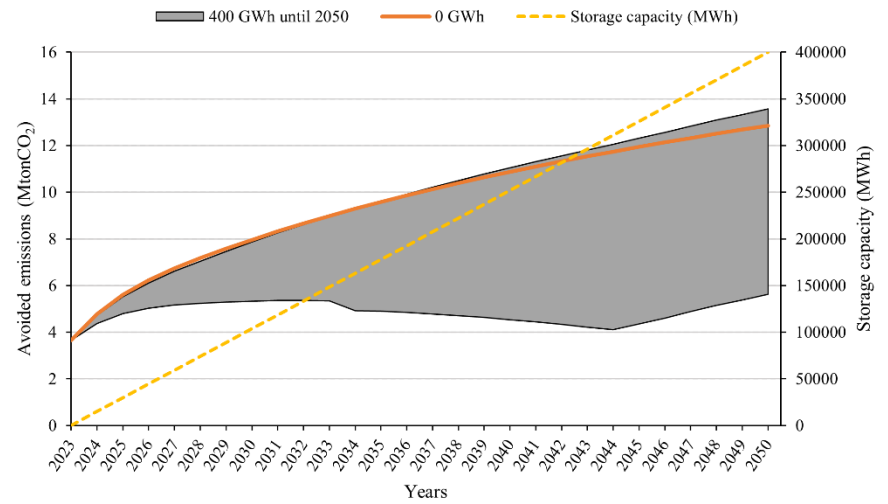
Results for scenario 1A



Results for scenario 2A

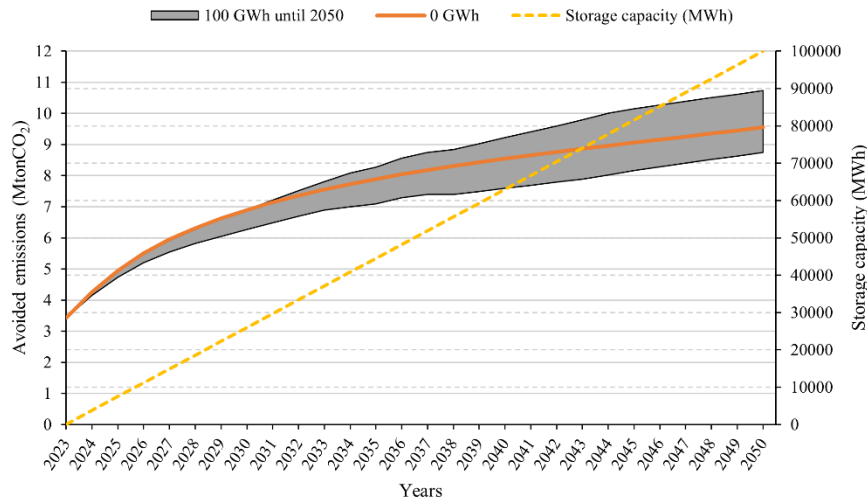


Results for scenario 3A

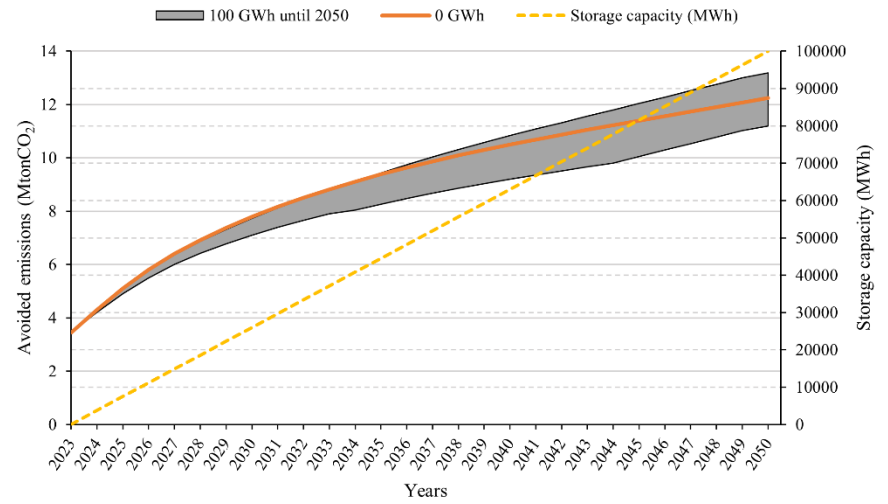


Results for scenario 4A

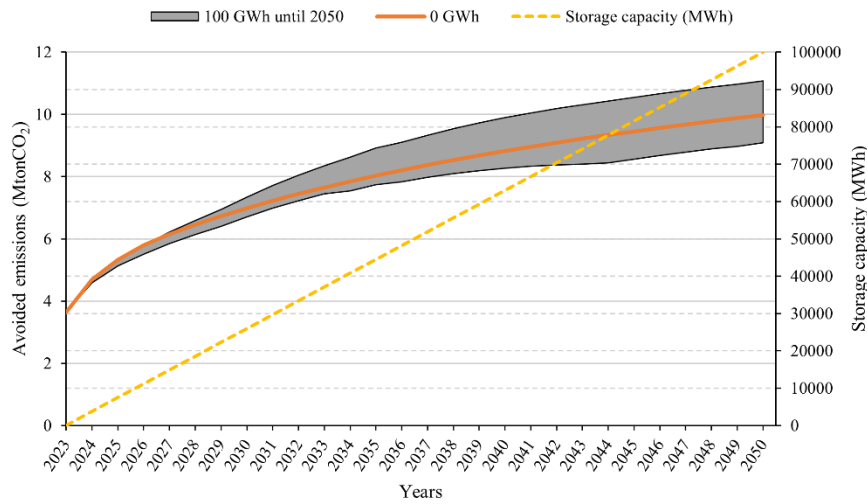
Figure 125 - Influence of the indirect emissions range on the expected avoided emissions with 400 GWh of storage capacity



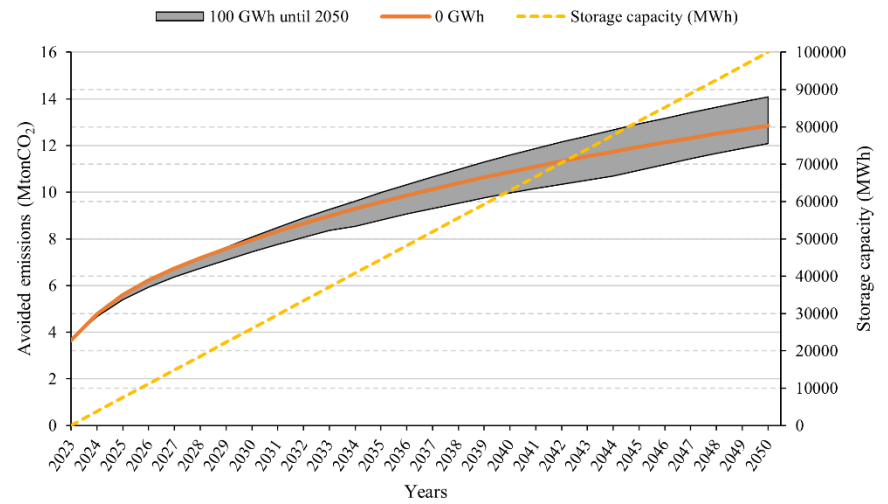
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A



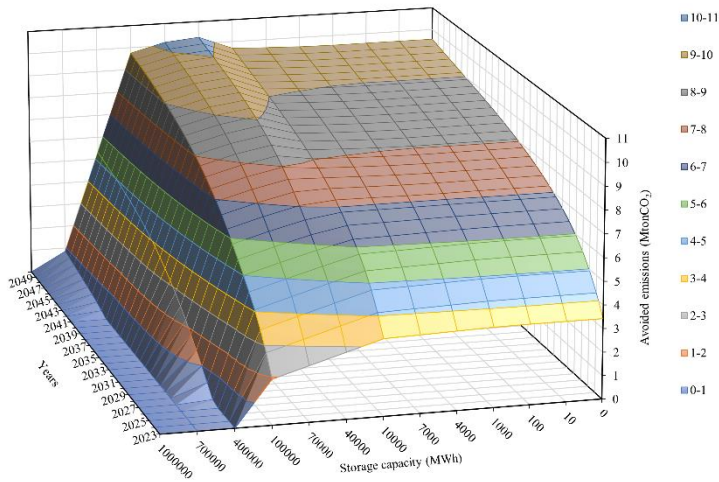
Results for scenario 4A

Figure 126 - Influence of the indirect emissions range on the expected avoided emissions with 100 GWh of storage capacity

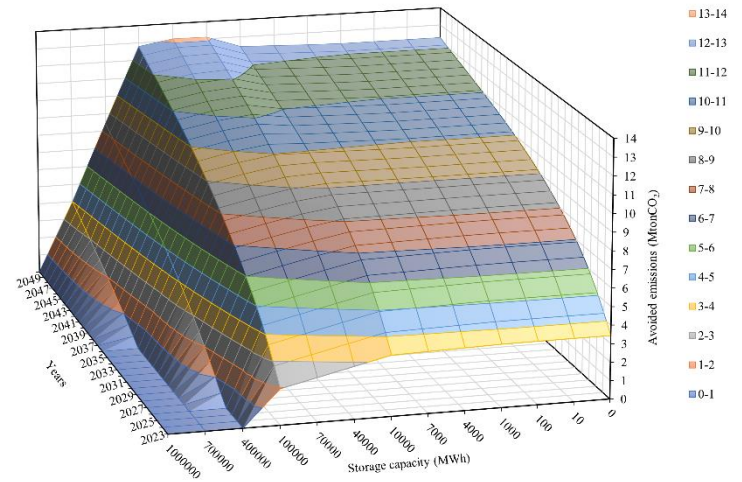
Let us revisit the situation discussed in section 5.7.5, assuming that the storage capacity is distributed across the networks according to the generation pattern. Moreover, an initial of 100 MWh in 2023 is considered, which increases until it reaches the value of 70 GWh in 2050, the limit value that produces benefits regarding avoided emissions.

Figure 127 shows the results of this scenario, which may be compared to the results of Figure 124, a similar situation but where the indirect emissions were not accounted for. Once again, distributing the storage capacity according to the generation pattern produces a positive impact, even when indirect emissions are considered. In this case, 70 GWh of storage capacity remains the capacity that promises the highest potential for avoiding emissions. The 40 GWh capacity in this analysis also presents similar results in avoided emissions as for 70 GWh of capacity.

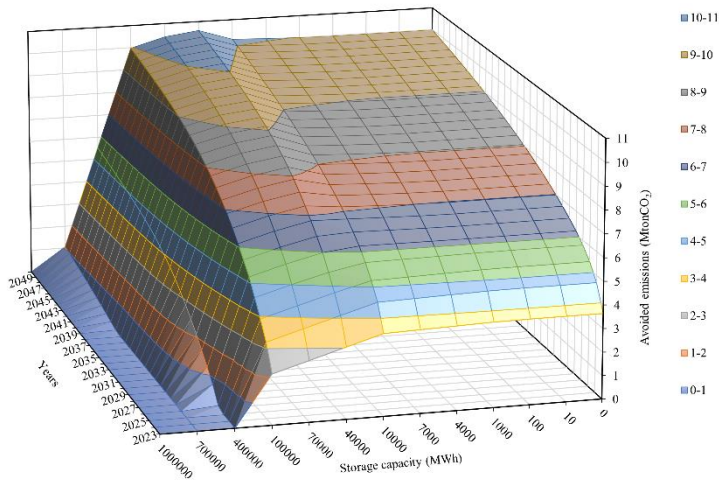
Figure 128 presents the results when utilizing the range of the emission factor (27 to 271 kgCO₂ per kWh). The findings indicate that installing an appropriate storage capacity over time and its distribution based on the generation pattern has a substantial and positive influence on reducing emissions. The positive effect occurs even in the worst case of indirect emissions. Scenario 3A stands out as the only one where the results are marginally less favourable than when storage is not considered, specifically due to the upper limit of emissions values (271 kgCO₂ per kWh) depicted by the lower line of the grey area. Nevertheless, it is important to note that this discrepancy is minimal and highly unlikely to occur in practice.



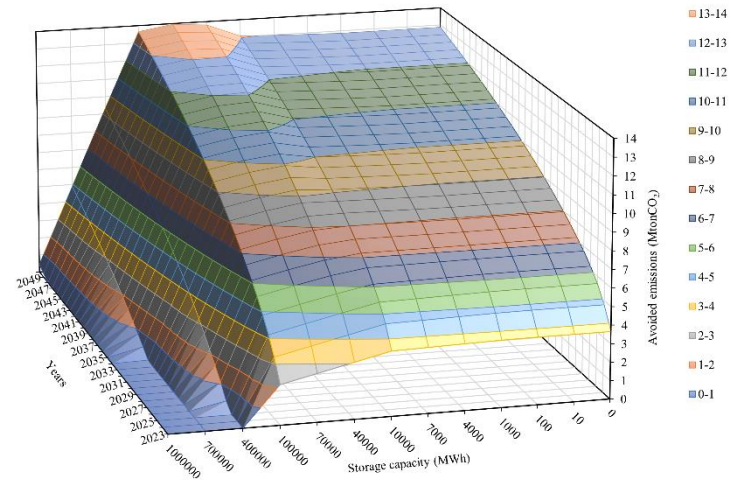
Results for scenario 1A



Results for scenario 2A

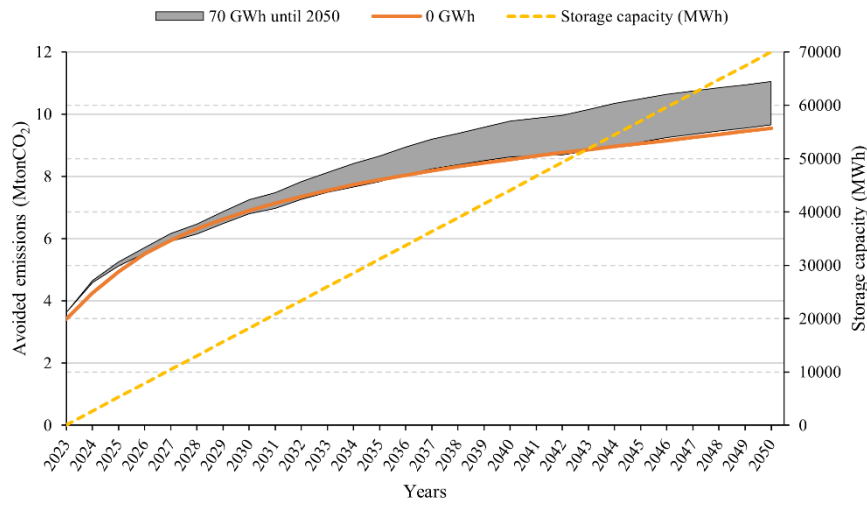


Results for scenario 3A

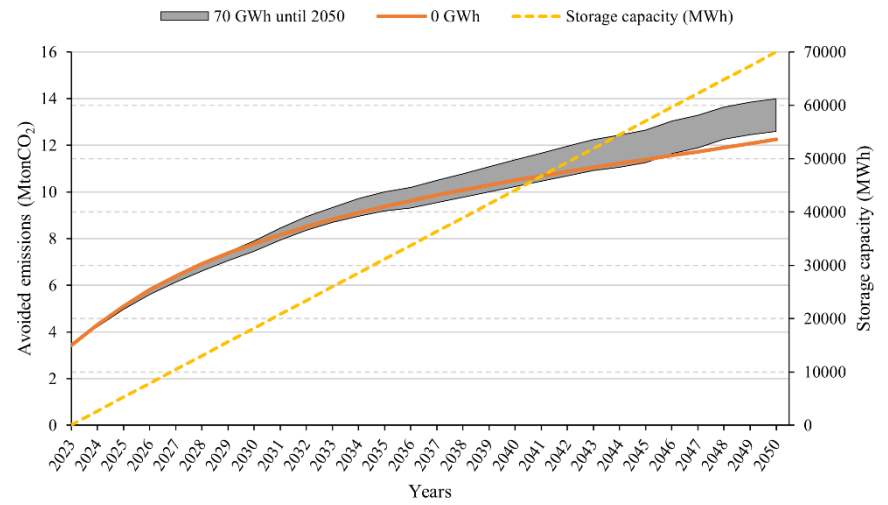


Results for scenario 4A

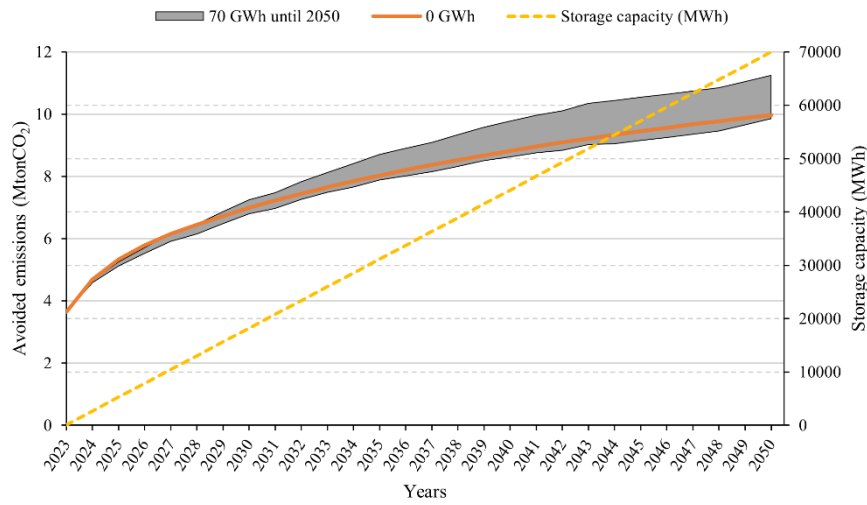
Figure 127 - Results adjusted for indirect emissions and storage capacity distributed according to the generation pattern



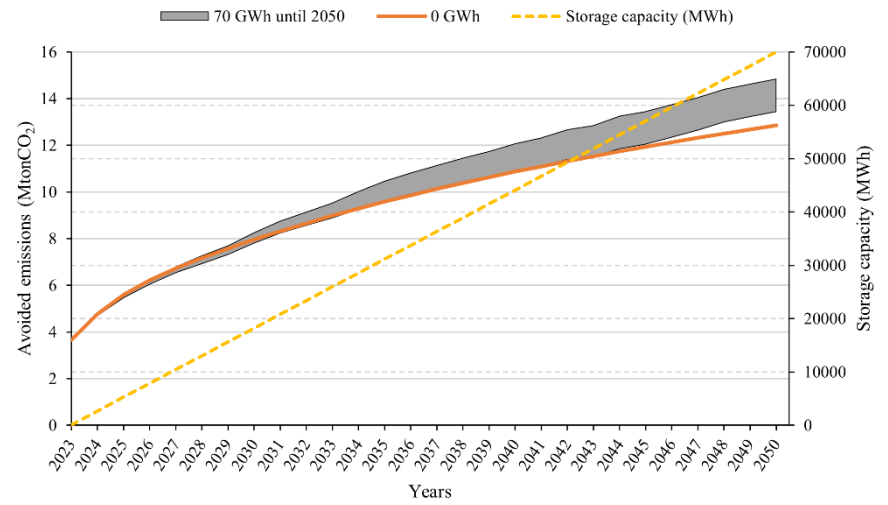
Results for scenario 1A



Results for scenario 2A



Results for scenario 3A



Results for scenario 4A

Figure 128 - Influence of the indirect emissions range on the expected avoided emissions for 70 GWh capacity distributed according to the generation pattern

An important aspect to consider in this analysis is the potential for changes in emissions associated with the manufacturing of lithium-ion batteries over time. As technology advances and electric grids become more efficient (given that battery manufacturing processes require substantial electricity), it is anticipated that the emissions related to the production of lithium-ion batteries, if they continue to be the leading technology, may decrease significantly [146], [147]. This study has been conducted using current emission values. Therefore, if indirect emissions decline in the future, the negative impact on the overall environmental footprint could be reduced. This situation indicates that the positive effects of avoided emissions from using battery-related storage systems may become even more promising.

5.7.7. The potential of the transport sector to avoid emissions

The transportation sector accounts for a significant part of energy consumption in Portugal. Since most cars use petroleum-derived fuels, their contribution to global emissions is substantial. Over the last few years, alternatives to traditional vehicles have been sought, mainly through the significant development of electric mobility.

As already discussed, electric mobility involves challenges for the electrical system, particularly concerning reducing respective emissions. Indeed, the transition to electric mobility will imply the need to generate more electricity and may increase the system load at some specific periods. This fact may delay the phase-out of electricity generation plants based on fossil fuels, particularly natural gas plants in Portugal's specific case. Therefore, the decarbonization of the electric power system tends to be delayed by the development of electric mobility. However, the potential negative impact on avoided emission in the early years can be offset by the reduction in consumption of fossil-based fuels, resulting in additional avoided emissions. Hence, this section aims to demonstrate the complementary avoided emissions that can be achieved through the transition to electrification in one of the largest sectors contributing to pollution.

According to statistics in [148], approximately 99% of vehicles in Portugal have historically been powered by gasoline or diesel. However, this percentage has slightly decreased in recent years, dropping to around 97%, as shown in Figure 129. Moreover, diesel-based cars have faced a significant decline in sales in recent years, as illustrated in Figure 130.

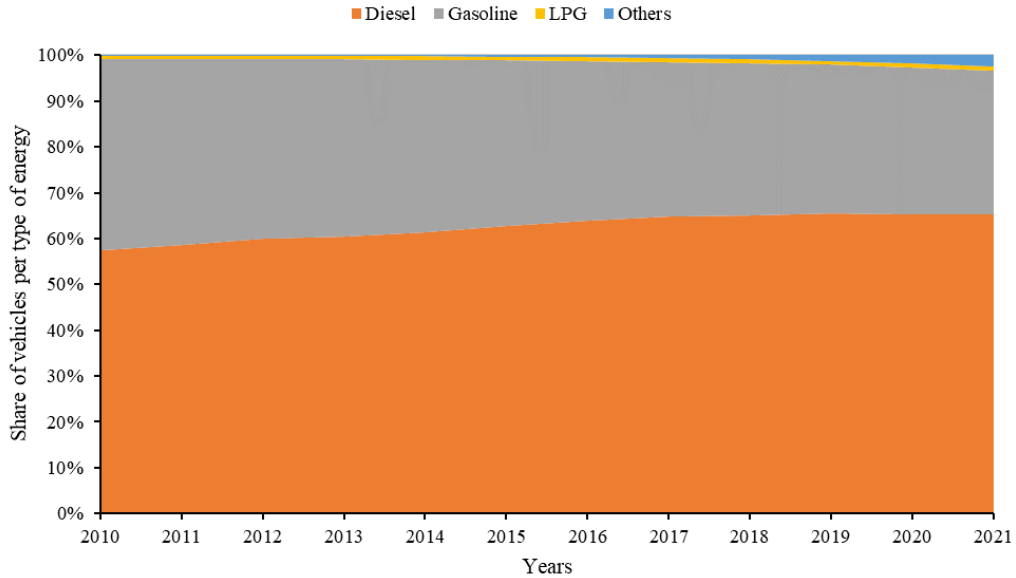


Figure 129 - Distribution of vehicles in Portugal categorized by the type of fuel

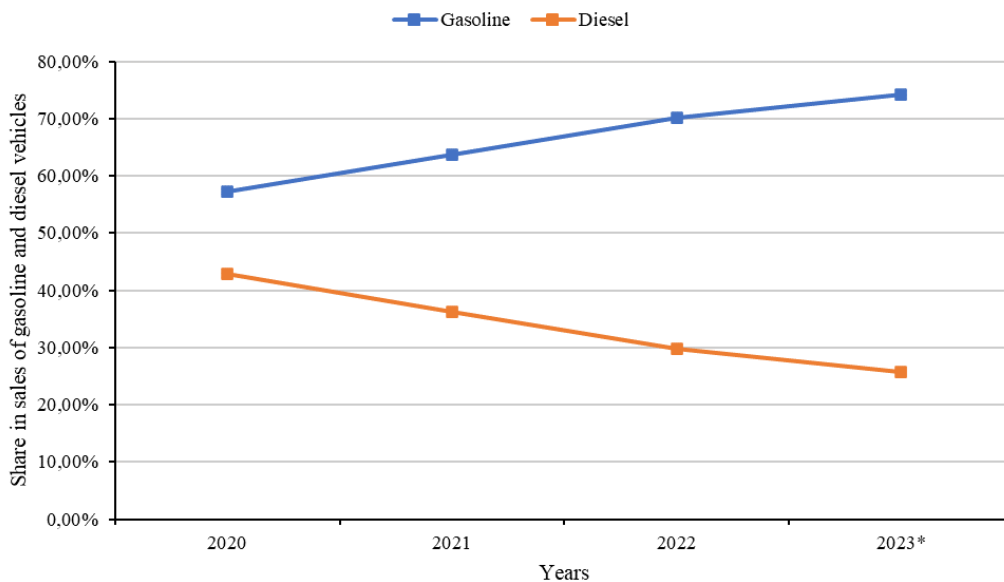


Figure 130 - Share in sales of gasoline and diesel vehicles *(2023 so far) (based on data from [149])

In line with this trend, the potential avoided emissions resulting from the transition of the transport sector were calculated. For this purpose, forecasts were made about the expected evolution of the number of electric vehicles in the fleet in Portugal and the consequent decrease (by replacement) of cars based on fossil fuels.

To achieve this objective, estimates regarding the fuel consumption of vehicles were obtained from two sources: i) statistics on the sale of fuels for the transportation sector [150] and ii) the annual distribution of circulating vehicles based on the type of fuel used [148].

The potential avoided emissions were then computed by assuming a proportional decrease in the usage of petrol or diesel vehicles, based on the scenarios illustrating the growth of the EV fleet outlined in section 5.2.4.2, Figure 96. For instance, if the projected EV fleet size for 2030 is around 850,000 vehicles, as indicated by the conservative scenario, it implies that 850,000 vehicles would no longer depend on petrol or diesel consumption. Using the data from Figure 130, a projection was carried out to determine the percentage of vehicles, classified by type, that are likely to be replaced by EVs. A power trendline was used to achieve this projection because it strongly correlates with the historical data. The resulting projections for the distribution of vehicles are presented in Figure 131. Note that the trend curves are inversely related, and the total proportion of gasoline and diesel vehicles consistently sums to 100% each year.

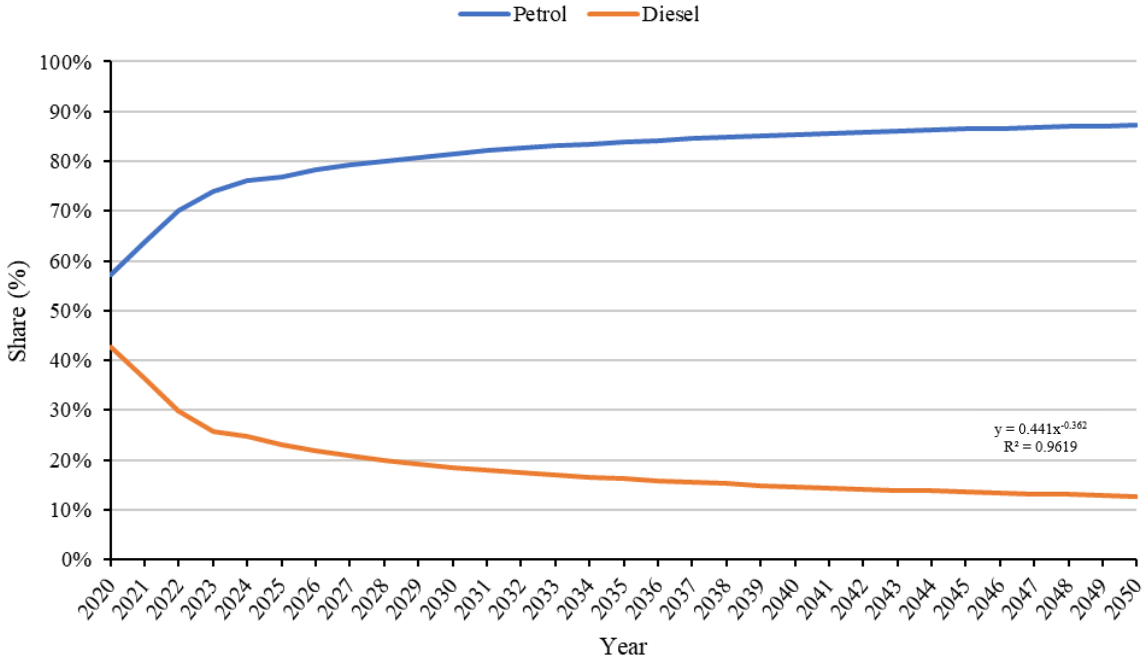


Figure 131 - Assumed tendency in the share of petrol and diesel vehicles

The estimation of the avoided emissions was calculated by:

$$AEve_y = (d_y \times ed \times cd + g_y \times eg \times cg) \times \frac{V_y}{10^9} \tag{48}$$

where: $AEve_y$ are the avoided emissions for year y (MtonCO₂);

d_y is the share, in %, of diesel vehicles in year y ;

ed is the specific emission factor for diesel (kgCO₂/kg);

cd is the average yearly consumption of diesel (kg/vehicle);

g_y is the share, in %, of gasoline vehicles in year y ;

eg is the specific emission factor for gasoline (kgCO₂/kg);

cg is the average yearly consumption of gasoline (kg/vehicle);

V_y is the predicted number of EV vehicles sales in year y .

The emissions factors for gasoline and diesel were considered from [142], and their respective densities from [151], [152]. The densities were needed to facilitate the calculus because statistics provided the amount of fuel in mass units, and the emissions factors came in per volume units. Table 29 shows the used emission factors.

Table 29 - Petrol and diesel emission factors and densities

	Emission factor		Density
	KgCO ₂ /l	KgCO ₂ /kg	Kg/l
Diesel	3.2	3.85	0.83
Petrol	2.8	3.78	0.74

Figure 132 presents the expected annual values of avoided emissions in the transport sector. Note that the results are presented in a graphical format, with the area varying based on the electric vehicle (EV) fleet growth scenario. Specifically, the lower line of the graph depicts results for scenarios characterized by a modest increase in the EV fleet. In contrast, the upper line corresponds to outcomes associated with the projections for a substantial increase in the EV fleet, as seen in Figure 96 of section 5.2.4.2.

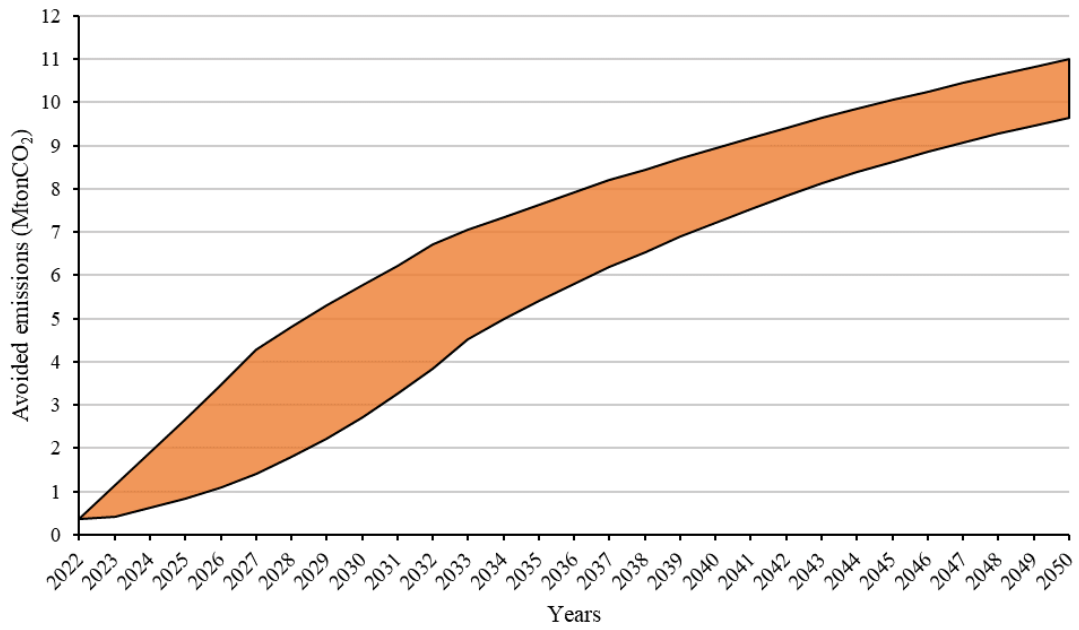


Figure 132 - Avoided emissions of the transport sector for Portugal's mainland

The potential of the transportation sector in terms of avoided emissions is substantial. By 2030, the transportation sector could potentially avoid emitting between 3 to 6 MtonCO₂, and this figure is projected to increase to a range of 9.5 to 11 MtonCO₂ by 2050.

6. CONCLUSIONS AND FUTURE WORKS

The need to decarbonise human activities and transition to clean energy sources has never been more urgent as we witness the impacts of climate change. The Paris Agreement, a landmark international accord, has set ambitious emission reduction goals, including halving emissions by 2030 and achieving net-zero emissions by 2050. These targets are crucial to limiting global warming to 1.5 °C or less and mitigating the severe consequences of climate change.

The generation, transmission, distribution and energy consumption are vital components of modern societies. However, a significant portion of our energy currently comes from fossil fuels, which release substantial amounts of greenhouse gases, exacerbating global warming. As the global population grows and living standards improve, energy demands are soaring, further intensifying our reliance on fossil fuels. Therefore, it is imperative to implement significant changes in the energy sector to mitigate greenhouse gas emissions.

Not only does the use of fossil energy contribute to environmental challenges brought on by climate change, but it also has detrimental health effects. Therefore, humanity is at a crossroads, and taking action towards decarbonisation is essential to prevent widespread disruptions and mitigate the worst consequences of climate change.

In recent years, the scientific community has made significant strides in the pursuit of decarbonisation, devoting considerable time and resources to the development of new technologies and strategies. As a result, many scientific publications, research projects, and patents have emerged. However, the vast amount of research conducted in this field has made it increasingly challenging to determine the true importance and practicality of proposed solutions.

A methodology based on two text-mining tools (TIM and VOSviewer) was developed and used in this work to identify and prioritise the domains of technologies that hold the most significant potential for achieving decarbonisation. The proposed approach starts with obtaining the documents (scientific publications, patents) that obey a carefully designed boolean search string prepared to capture the desired information. It is essential to point out that the sets of documents obtained to be analysed by VOSviewer and by TIM were different since different

databases were used (in this case, the WoS database for VOSviewer and the SCOPUS, CORDIS, and PATSTAT databases for TIM). The obtained documents were then processed to attain significant terms (one or more words), specifically the “Author Keywords” and their occurrence in the VOSviewer case and the “Relevant Keywords” and their relevance in the TIM software.

The text-mining software (TIM and VOSviewer) retrieved several terms that were not relevant to the intended study. Additionally, multiple versions of similar meanings (such as PV system, photovoltaic, photovoltaics, solar PV, etc.) appeared, requiring the development of a procedure to combine them. As a result, programs based on Python code were developed to handle these terms. These programs eliminated the irrelevant terms and consolidated those with identical meanings. In this process, a semantic dictionary was crucial, which was developed using a semi-automatic method that combined a program created in Python with human intervention.

The developed methodology was utilised for 2011-2021, identifying 87,212 documents from the selected databases. Of these, 59,411 were processed through TIM software, while the remaining 27,801 were treated by VOSviewer software. It is worth noting that a consistent upward trend in the number of documents retrieved each year, particularly in scientific papers, was verified. The bibliometric analysis done by TIM and VOSviewer software retrieved 793,700 keywords (689,075 from TIM and 104,625 from VOSviewer). After processing the terms obtained (elimination of repeated terms and those that do not make sense for the study and aggregation of those with similar meaning), 4,300 terms were accepted, divided into 426 sets with similar semantic meanings. These sets were then gathered into 41 domains, of which 39 were assumed to be technological.

The relevance (TIM) and occurrence (VOSviewer) values associated with each domain were assessed. The result showed increased values for most domains from 2011 to 2021. Moreover, the “policy and circular measures” domain has the highest accumulated value of “relevance” and the second highest accumulated value of “occurrence”. However, “policy and circular measures” and “natural carbon capture and storage” domains are not aligned with the logic of technology domains. Consequently, they have been excluded from the subsequent analysis. The domains “energy efficiency and management”, “not specified renewables”, “carbon capture, storage and use”, “hydrogen”, “biofuel”, “energy storage”, and “low carbon and autonomous transportation” stood on top of the absolute relevance and occurrence indicators. An important finding from this analysis is that the combined relevance and

occurrence values of the top 20 domains account for 87.1% and 93% of the total accumulated relevance and occurrence values, respectively. Furthermore, 19 of those 20 domains coincide. Additionally, the ten most relevant domains represent almost two-thirds of the total accumulated relevance, while the ten most occurrent domains represent three-quarters of total accumulated occurrence. Furthermore, eight of the top ten more relevant and more occurrent domains coincide, representing 57.7% of the total accumulated relevance and 60.9% of the total accumulated occurrence. The “energy transmission infrastructure” and the “buildings - passive measures” domains belong to the top ten domains with more relevance but not to the top ten more occurrent domains. Conversely, “biofuel” and “wind energy” domains belong to the top ten of most occurrent domains but do not integrate the top ten of the domains with more relevance.

In terms of relative values, the domains “carbon capture, storage, and use”, “energy efficiency and management”, “biofuel”, and “nuclear power” have experienced a decrease in the indicators. On the other hand, the domains “hydrogen”, “unspecified renewables”, “low-carbon and autonomous transportation”, “energy storage”, and “electrification” have gained relative interest. In the end, we concluded that eight domains stood out regarding the relative accumulated scores (of both relevance and occurrence): “carbon capture, storage, and use”, “energy efficiency and management”, “hydrogen”, “unspecified renewables”, “low-carbon and autonomous transportation”, “energy storage”, “digitalisation and smart systems”, and “photovoltaic”.

The readiness of the specified technology domains was determined by calculating the average Technology Readiness Level (TRL) for a specific set of innovative technologies associated with those domains. The information regarding the innovative technologies considered in each domain was obtained from a database linked to the IEA’s Energy Technology Perspectives 2020. The technologies within the database were assigned to specific technology domains based on their unique characteristics. Moreover, the 368 individual technologies were associated with 35 of the defined domains. Indeed, no technologies were associated with the “policy and circular measures”, “natural carbon capture and storage”, “shale natural gas”, “natural gas power generation”, “agricultural sector”, and “not specified distributed generation” domains. Domains such as “hydrogen technology,” “carbon capture, storage and use,” “not specified renewable,” “energy storage,” and “low carbon transportation” have a relatively high number of associated technologies.

On the other hand, domains like “hydropower,” “other generation,” “energy community,” and “hybrid generation system” have a smaller number of associated technologies. Moreover, approximately half (51.4%) of the domains have an average TRL equal to or greater than 7. Note that four domains (11.4%) still have an average TRL close to 7 (greater than 6.9), which means that practically 2/3 of domains have an average TRL that corresponds (or almost corresponds) to the commercial stage. It is important to note that domains with more associated technologies may still have a significant percentage of technologies in the commercial stage. For instance, “energy storage” has over 70% of its related technologies in the commercial stage, while “not specified renewables” has 60% of its technologies in the same stage. Conversely, “hydrogen technology” has more than 60% of its 41 technologies in a non-commercial stage. Note that some domains, such as “nuclear power” or “marine energy”, present a relatively low average value of TRL, resulting from a high percentage of technologies in the not-commercial stage.

The intersection between the specified technology domains and a predefined set of decarbonisation pathways revealed that out of the initial 41 domains, only 12 are included within each decarbonisation strategy’s top five relevant domains. Moreover, only 11 domains fit the concept of technology domains since the “policy and circular measures” domain is associated with some decarbonising topologies. Moreover, only one of those 12 domains, specifically the “energy transmission infrastructure” domain, is not among the 20 domains with the highest accumulated relevance and occurrence values.

The readiness assessment of the decarbonisation pathways relied on utilising the information related to the respective top five significant technology domains. This information allowed valuable insights into the technological landscape of decarbonisation pathways, facilitating a comprehensive understanding of the distribution and maturity of associated technologies. Based on the analysis findings, the “Electrification of uses” pathway is the most favourable option. Indeed, despite including fewer associated technologies, this pathway has the highest average TRL value and the highest percentage of technologies in the commercial stage. As a result, it can be inferred that this decarbonisation approach is more resilient and promising. The “Technology breakthrough” and “Decarbonisation of electricity” pathways share many similarities regarding the number and percentage of associated technologies in commercial status. However, the “Decarbonisation of electricity” pathway has a slightly higher average TRL value, making it a marginally stronger option in terms of technological readiness. Likewise, the “Integrated systems” and “Demand and Co-benefits” pathways have the same

number of associated technologies and the same percentage of technologies in commercial status, which is less than 50%. Their average TRL values are the second highest among the pathways analysed. Therefore, these pathways are less promising than the “Electrification of uses” and “Decarbonisation of electricity” pathways. The “Land use and circularity” pathway is characterised by having the most significant number of associated technologies and the highest percentage of technologies in commercial status. However, it has the lowest average TRL value, suggesting that further development and improvements are needed for this pathway to be as effective and resilient as the others.

In addition to the readiness of decarbonisation pathways, the associated risk and potential for decarbonisation was also assessed. The risk was evaluated by intersecting the readiness and the ratio between relevance and occurrence rankings of the five more relevant domains that support each decarbonisation pathway. The potential for decarbonisation was assessed using information made available by the IPCC regarding the potential of some technologies for reducing net CO₂ emissions by 2030. A global assessment of the pathways is presented in Table 30.

The “Electrification of uses” pathway emerged with a higher readiness level and higher potential for decarbonising. At the same time, this pathway presents the lowest associated risk. Conversely, the “Technology breakthrough” and “Land use & circularity” pathways are the least well-positioned. Moreover, despite extensive research efforts, the “Technology breakthrough” pathway exhibits a higher level of risk compared to other pathways, albeit lower than the “Land use & circularity” and “Decarbonisation of electricity” pathways.

Table 30 - Summary of results of each decarbonisation pathway

Domain	Decarbonisation pathway					
	Integrated Systems	Technology breakthrough	Demand co-benefits	Decarbonisation of electricity	Electrification of uses	Land use & circularity
Readiness (average TRL)	2	5	2	4	1	6
Potential	2	5	2	5	1	4
Sum	4	10	4	9	2	10
Rank	2	5	2	4	1	5
Risk level	--	---	--	----	-	----

An important finding from the analysis is that the electrification of human activities is fundamental to the decarbonisation process. Therefore, in the second part of this work, a model was proposed and used to estimate expected avoided emissions for the Portuguese electric power system. Several scenarios were created regarding the prospects for electricity consumption and non-conventional generation growth. Moreover, sub-scenarios have been defined to account for the impact on the consumption profile that may result from the expected

expansion of electric mobility, namely from diverse patterns of EV charging. Several sensitive analyses were performed in addition to the results obtained.

As expected, the results provide evidence that the objective of boosting the installed capacity of non-conventional (renewable) generation, particularly wind and photovoltaic-based systems, leads to a significant value of expected avoided emissions. In the best-case scenario, an annual value of avoided emissions of approximately 8 MtonCO₂ is forecasted for 2030, with an even higher estimation of about 12.9 MtonCO₂ for 2050. The cumulative expected avoided emissions from 2023 to 2050 amounts to approximately 266.5 MtonsCO₂. Conversely, in the more pessimistic scenario, it is estimated that annual avoided emissions would be around 6.9 MtonsCO₂ in 2030, increasing slightly to 9.6 MtonsCO₂ in 2050. Under this scenario, the expected emissions reduction from 2023 to 2050 would be 214.2 million tons of CO₂. It should be noted that these results assume the absence of storage capacity in the power system.

The deployment of storage systems has demonstrated potential for enhancing the value of avoided emissions. However, it is crucial to consider that these benefits could be realised in the most optimistic scenario as early as 2028. Conversely, in a less favourable scenario, it might take until after 2039 to truly experience their effects. Depending on the specific scenario, the benefits of implementing storage systems can potentially reduce emissions in a value that ranges from 4.5% to 12.1% in accumulated values over the 2023-2050 period. It is important to highlight that storage makes a larger impact as the years advance, and these values can range from 10% to 17.1% in 2050, depending on the scenario. Furthermore, it is important to highlight that significant benefits in avoided losses are only realised when the installed capacity of storage systems exceeds 10 GWh. As the capacity expands, the gains continue to escalate significantly until the limit of 400 GWh. It should be emphasised that no additional benefits occur from adding storage capacity above the 400 GWh threshold. However, it is worth highlighting that this observation applies to most scenarios, except where electricity consumption is substantially increased, and there is modest growth in non-conventional generation capacity. In this specific scenario, the benefits of adding storage capacity do not significantly increase for values exceeding 100 GWh.

The potential impact of electric mobility charging patterns on electricity consumption has implications for the expected avoided emissions due to the more significant gap between electricity generation and consumption. Once again, the impact depends on the specific scenario considered. For instance, when no storage systems are included, the expected value of accumulated avoided emissions decreases by 5% to 7.7%, for the case where the charging of

EV concentrates more at the peak hours. If the charging concentrates more at nighttime, this value ranges from 8.2% to 9.6%. Network storage capacity is crucial, particularly when EVs are charged predominantly at night. In the least favourable scenario (where electricity consumption is substantially increased, and there is modest growth in non-conventional generation capacity), the expected value of avoided emissions rises by 20% for the year 2050 compared to the situation without storage systems. In the best scenario (low increase in electricity consumption and modest growth in non-conventional generation capacity), the avoided emissions increase amounts to approximately 32.4% in the same terms. Interestingly, the limit for the installed storage capacity in the scenario represented by a high increase in electricity consumption and conservative growth in non-conventional generation becomes 400 GWh, like in the other scenarios.

Sensitive analysis revealed that how the non-conventional generation capacity is distributed across the networks is crucial in avoiding emissions values. However, the study is limited by the developed model, which does not consider the energy flowing to upstream networks, making it impossible to assess this issue thoroughly. Nevertheless, when considering storage, this limitation is partially overcome once the surpluses after charging the storage systems tend to be minor, resulting in significant gains that can potentially reach an additional 3.5% reduction in emissions by 2050.

According to a sensitive analysis study, strategically locating storage systems throughout the networks is crucial to maximising their impact on avoided emissions. The study suggests that installing 70 GWh of storage capacity, distributed in alignment with energy generation patterns, can yield comparable or even better results than the assumed 400 GWh capacity in our base scenarios.

The importance of internalising the indirect emissions related to battery manufacturing was also recognised when evaluating the relevance of the distribution of storage systems across the networks. The large-scale deployment of storage systems in the base scenarios appears challenging due to indirect emissions. Indeed, the results provide evidence that storage capacity installation may even increase emissions. However, by strategically locating storage systems within the network, we can successfully mitigate the impact of indirect emissions and ensure the practicality and viability of storage systems.

During this work, several issues were identified that deserve further study in future work, namely:

- to further enhance the model, it is crucial to consider the possibility of energy flowing upstream from the point of generation within the networks. This aspect is particularly significant to comprehensively evaluate the potential impact of distributing non-conventional generation across the networks.
- While this dissertation primarily focuses on the environmental aspect of potentially avoided emissions, exploring the technical aspect of integrating storage systems into the power system and identifying their optimal locations would be beneficial. This analysis could examine whether it is more advantageous to position storage systems near consumption points or wind and PV farm substations. Conducting such research would provide valuable insights into the technical considerations involved in integrating storage systems.
- Another interesting aspect involves the political incentives to promote such technologies' dissemination and effective utilisation.

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APPENDIXES

APPENDIX A

DESCRIPTION OF THE BIBLIOMETRIC ANALYSIS TOOLS (TIM AND VOSVIEWER)

Bibliometric analysis is widely used in quantitative analysis of scientific publications to identify and predict trends in specific research fields. It proves to be an effective literature review method, especially as the number of publications increases [153]. Text mining programs are used as tools and support the application of the bibliometric method.

TIM – “Tools for Innovating Monitoring”

The TIM software is based on semantic analysis and data mining, allowing the treatment of complex data sets and the tracking of established and emerging technologies [154]. TIM may count activity levels in the R&D bibliography, patents, and research projects funded by the European Union. Therefore, TIM may be used to identify collaboration patterns, technological changes, and evolution, potentially tracking the progression of keywords over time by domain, allowing clustering by topics, institutions, and geographic regions.

To count the previously referred activity levels, the TIM retrieves bibliometric data from several sources, namely [154]: i) from the SCOPUS database of peer-reviewed scientific journals; ii) from the database of European Union (EU) research projects CORDIS; iii) and from the PATSTAT, a vast database of patents.

Thus, TIM can monitor technological development trends by identifying relevant keywords and lead players by country, region, and sector and comparing them with other players and technologies [155].

Using the TIM software implies a suitable search string is established to retrieve data from scientific publications, patents, and EU projects [155], [156]. As shown in Figure 133, the search string comprises a combination of terms, fields, and boolean operators. The Boolean operators, namely the operators (AND), (OR), and (NOT), allow the presence or absence of specific terms to be imposed on the result of the search.

The terms define what is intended, the fields designate where we want to search for the terms, and the operators combine multiple fields and/or multiple terms to make more specific searches. The most important searchable fields are presented in Table 31.

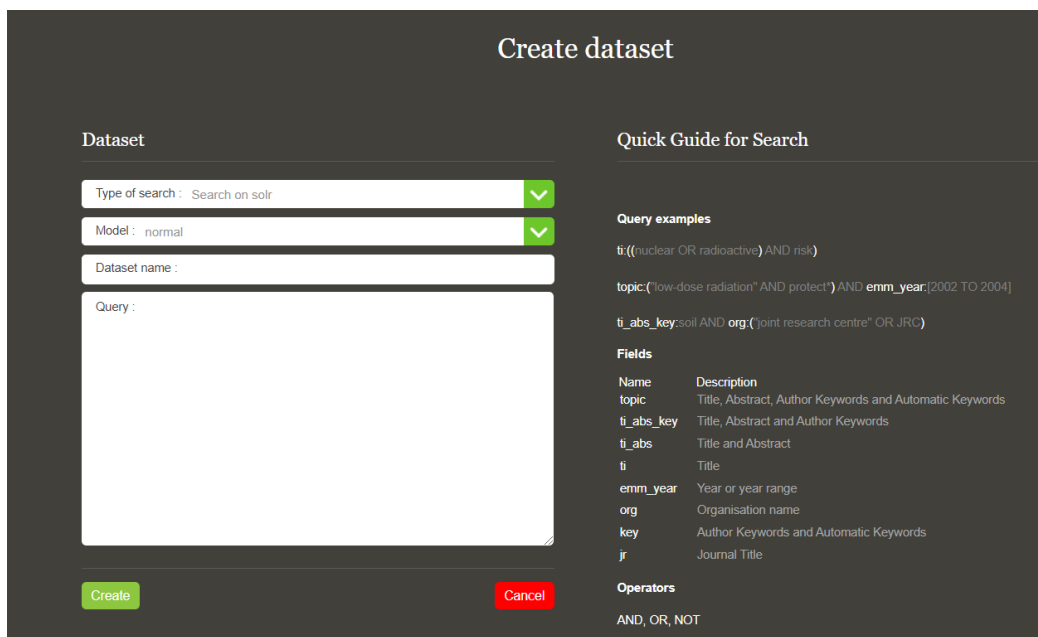


Figure 133 - Search on TIM

Table 31 - Most important fields in TIM search

Field	Searches in
topic	Title, Abstract, Author Keywords, and Automatic Keywords
ti_abs_key	Title, Abstract, and Author Keywords
ti	Title
emm_year	A year or year range
class	Filter by document type

The string defined allows requesting information from the databases considering constraints related to a specific temporal period, a language, an area of knowledge, etc.

The TIM software applies stemming and lemmatization to search terms. The first concept is a process that reduces the word to its radical. This reduction may be successful on some occasions, but not always. For example, searching for the term “studies” will find documents containing the stem “studi”. However, searching for the term “studying” will find documents containing the stem “study”. The second search uses the context in which the word is being used (morphological analysis), meaning that, for instance, studies and studying have the same lemma (“study”).

Term modifiers may also be used, which allow the user to introduce flexibility or precision into the search terms. This flexibility is achieved using wildcard characters, such as the asterisk (*) and the tilde (~), as described in Table 32.

Table 32 - Term Modifiers

Modifier	Utility	Example
*	used to represent a set of sequential characters (including zero characters)	electroly* will correspond to electrolyte, electrolytic, among others.
~3	A search term followed by a tilde (~) and a numeric value indicates that these words can be separated by a maximum distance equal to the numeric value.	“CO2 capture” ~ 5 includes documents that have the term “CO2 capture” but also the text “CO2 utilization and capture”.

The search result based on the search string is a dataset corresponding to an aggregation of documents extracted from the databases, as Figure 134 shows. The information retrieved by TIM may effectively convey a quick first impression of the ‘big picture’ at high aggregation levels, even if it may appear somewhat ambiguous upon more detailed scrutiny [155].

A limitation of this software is related to the fact that the dataset can contain a maximum of 10,000 documents. Therefore, if the validated dataset has more than 10,000 documents, the string must be refined to limit the number of results. Otherwise, it will not be possible to proceed with the analysis and processing of the data.

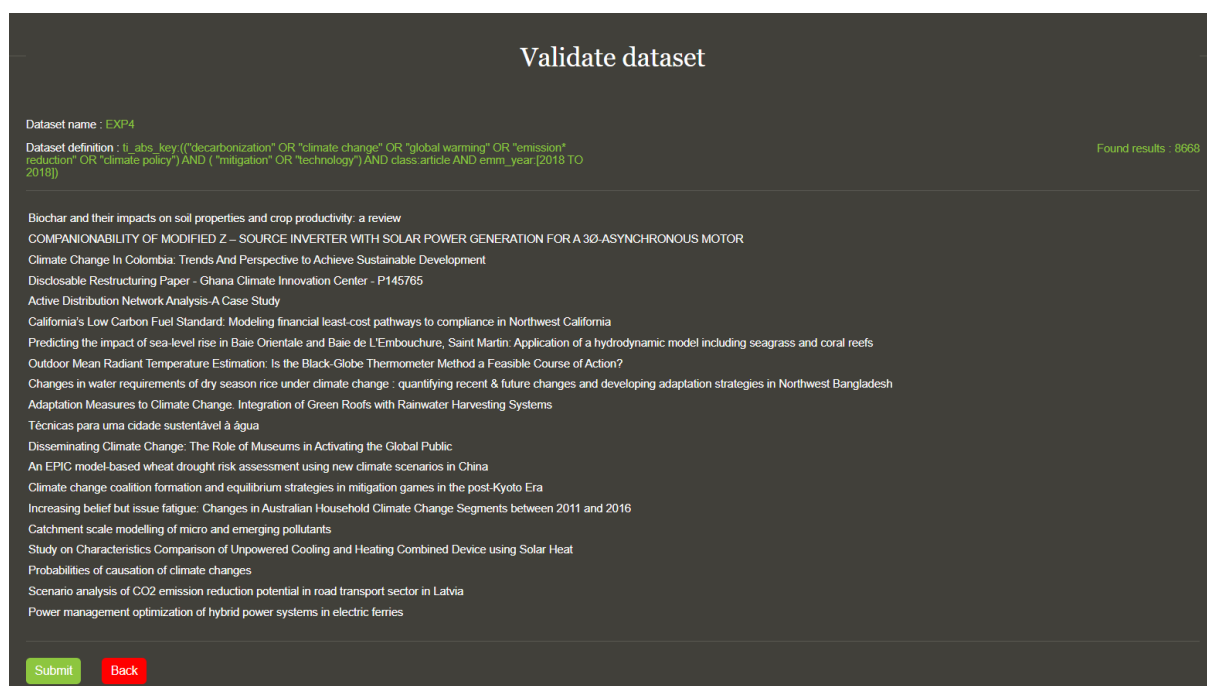


Figure 134 - Example of a dataset resulting from a TIM search

The information in the dataset may be presented by using a multitude of views, as explained in Table 33:

Table 33 - Possible views of TIM software

Page	Subpage	Description
Space Page	Datasetgram	Nodes are the datasets created, and their size is proportional to the number of documents. Borders represent the documents in common.
	News Trends	News trends for all datasets associated with a news category. Available if the news category has been previously created.
	Dataset Matrix (<i>L</i>)	Matrix displaying all datasets. The intersection of two datasets represents the number of documents in common. A list of all the datasets is also available.
Organization	Dataset Info	Information about the dataset, namely: name, search string, creation, and modification date, distribution in types of documents, trend in time, etc.
	Organizations	The nodes are the Top 100 Organisations. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s).
Location	Cities	The nodes are the Top 100 cities where the Organisations (processed) are located. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s) between the organizations in those cities.
	Countries	The nodes are the countries where the Organisations are located. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s) between the organizations in those countries.
	EU/World	The nodes are the EU countries (all in one node) or the rest of the world countries where the Organisations (processed) are located. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s) between the organizations in those countries.
	EU Countries	The nodes are the EU countries where the Organisations are located. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s) between the organizations in the EU countries.
	NUTS2	The nodes are the Nuts2 regions where the Organisations (processed) are located. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s) between the organizations in those regions of the EU.
	NUTS3	The nodes are the Nuts3 regions where the Organisations (processed) are located. The edges represent Co-patenting and/or Co-publishing and/or Co-participation in an EU research project(s) between the organizations in those regions of the EU.
	Map	The location of the Organisations (processed) in a geographical map based on the city's location. The circles or pointers on the map indicate the number of documents in the area that appear when hovering.
	EU/World Map	Location of the Organisations (processed) in a geographical map with all the EU as one location. The circles or pointers on the map indicate the number of documents in the area that appear when hovering. Documents from organizations in the EU are forced to emerge as one unique location in Brussels.
Topic	Detailed classification patent	The nodes are the CPC classification symbol (full version) to which the patent is attributed. The edges represent the co-occurrence of two CPC classes in the same patent, i.e., inventions that belong to both subjects. (Only available for patents)

	Author keywords (<i>S</i>)	The nodes are the Author keywords attributed by the authors to their publications. The edges represent the co-occurrence of two author keywords in the same publication. (Only available for scientific publications)
	Automatic keywords	The nodes are the Automatic keywords generated by language processing algorithms for all types of documents. The edges represent the co-occurrence of two automatic keywords in the same document.
	Relevant Keywords	Most relevant keywords in the dataset and their relevance. Language processing algorithms generate these keywords to represent the dataset as a whole.
	Patent classification (<i>adv</i>)	The nodes are the CPC subclasses (5 digits + name) to which the patent is attributed. The edges represent the co-occurrence of two CPC classes in the same patent, i.e., inventions that belong to both subjects. (Only available for patents)
	Author Keywords (Raw) (<i>adv</i>)	The nodes are the raw version of the Author keywords attributed by the authors to their publications. The edges represent the co-occurrence of two author keywords in the same publication. (Only available for scientific publications)
	Clusters (<i>adv</i>)	The nodes are clusters of documents based on their semantic similarity. The name of the cluster is the most relevant keyword of the cluster of documents. The edges represent the semantic similarity between clusters of documents.
	Author Keywords List (Raw) (<i>L</i>)	List of Author keywords (raw) attributed by the authors to their publications.
	Automatic Keyword List (<i>L</i>)	List of the Automatic keywords attributed by TIM to all types of documents.
Quantitative Analysis	Type of documents (<i>adv</i>)	Chart and table of the distribution of each type of document per year in the dataset.
	Time series (<i>adv</i>)	Chart and table of the evolution in time of the number of documents per organization.
News	News (<i>adv</i>)	Latest news for the EMM category assigned to the dataset. (Only available if a news category has been previously created.)
	News Trends (<i>adv</i>)	Evolution in time of the number of news items retrieved (Only available if a news category has been previously created.)
Miscellaneous	Years	The nodes are the publication year of the publication, priority year of the patent, or the starting year of the EU project. There are no edges in the graph, as a document cannot have two different years. Use this graph for filtering purposes.
	Type of documents	The nodes are the types of documents in the dataset. There are no edges in the graph, as a document cannot be of two different types. Use this graph for filtering purposes.
	Data source	The nodes are the original database from where the documents come from. There are no edges in the graph, as a document cannot come from two different databases. Use this graph for filtering purposes.
	Documents	List of documents in the dataset.
Data (<i>adv</i>)	Field Viewer (<i>adv</i>)	All fields and values of the dataset are displayed in a user-friendly and filterable way.

	Main fields (<i>L</i>)	Main fields (title and descriptions) and dataset values are displayed in a user-friendly and filterable way.
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The subpage (view) “Topic Page” is particularly relevant for this project. In this view, it is possible to obtain information about, among others: “relevant keywords” and “author’s keywords”.

- “Author’s keywords”: this view shows information based on keywords assigned by the authors to their publications.
- “Relevant Keywords” displays the most relevant keywords in the dataset, generated by language processing algorithms to represent the dataset as a whole. These keywords have an associated rank that measures the “relevance” of each term. That rank is calculated as:

$$Relevance = TF \times IDF \times modifier$$

Where:

- TF is the Term frequency, calculated by:

$$TF = \frac{\text{number of times a term appears in a documents}}{\text{total number of terms in the documents}}$$

- IDF is the Inverse Document Frequency, calculated by:

$$IDF = \log\left(\frac{\text{number of documents in the collection}}{\text{number of documents in the collection containing the term}}\right)$$

- The “modifier” gives more or less weight to the terms depending on where they are found (title, abstract, or keyword). In this specific case, the modifier is calculated as follows: Title: 1 Abstract: 0.5 Keyword: 2 This is made so that the “important” words are attributed a higher rank.

More on the TF-IDF algorithm can be found in [157].

Figure 135 shows an example of relevant keywords for a dataset previously obtained following the procedure described above.

It is important to stress that TIM works on a combination of nodes (bubbles) and edges (lines). The node size is based on the number of publications/documents retrieved by a semantic search/query. An edge between 2 nodes (countries, organizations, keywords, etc.) means co-occurrence of documents (articles, patents, reviews, projects), meaning that some documents are in common (co-filed patent, co-publication). Therefore, the TIM software also allows the visualization of the information in a network graph, as shown in Figure 136. In this case, what a node represents depends on the selected visualization. For example, when viewing the page “Countries” within the page “Location”, each node represents a country. The size of each node corresponds to the number of documents associated with that node, and the edges generally

correspond to documents from the two nodes. The density of each edge represents the number of documents in common.

Entries: 104878

Keyword	Relevance
carbon emission (CE)	337
low carbon (LC)	337
2030	250
2050	190
emission reduction (ER)	190
global warming (GW)	174
sustainable energy	145
de carbonization	119
global warming potential ...	94
renewable energy (RE)	93
paris agreement (PA)	89
sustainable developmen...	89
energy system (ES)	87
fossil fuel (FF)	85
carbon capture storage (...)	83
electric vehicle (EV)	78
kilo watt hours (KWH)	70
nationally determined co...	69
energy transmitter (ET)	67
invention	62
de carbonisation	56
reducing carbon emissio...	54

Figure 135 - Example of relevant keywords in a specific dataset

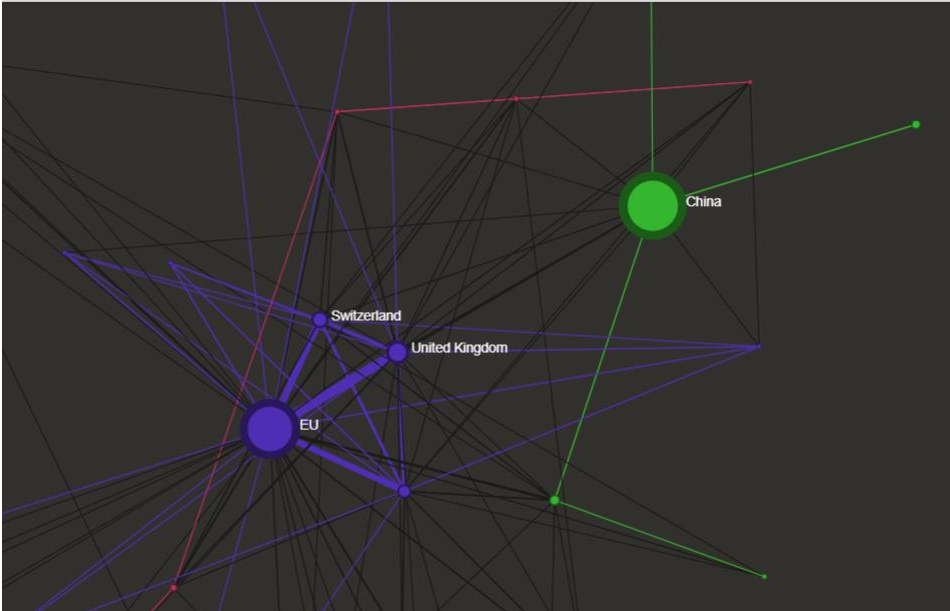


Figure 136 - View by location and countries in TIM software

VOSviewer

In VOSviewer, the dataset to be analyzed must be previously extracted from one of the following databases: Web of Science, Scopus, PubMed, RIS, or Crossref JSON.

The Web of Science (WoS) was the chosen database in this work, providing essential data for bibliometric analyses, including publication titles, authors, institutions, countries, abstracts, and keywords. The search in this database can be performed using a string similar to the one used in the TIM software, as seen in Figure 137.



Figure 137 - Search on WoS

The previous procedure allows for obtaining the dataset of documents that respect the search conditions. The obtained dataset must then be downloaded using the tab-delimited file format and the “Full record and cited references” options, as shown in Figure 138. It is important to stress that the Web of Science requires that the downloaded data contain information from a maximum of 500 documents. Therefore, when the dataset has more than 500 documents, the download must be done in multiple batches (each batch must be saved in a separate file).

After obtaining the dataset, the VOSviewer software proceeds with the bibliometric analysis. As Figure 139 shows, VOSviewer supports three types of maps: map based on network data, bibliographic data, or text data. The user must define the kind of map that is to be used.

After selecting the map type, the files extracted from the WoS must be inserted into the VOSviewer software, as shown in Figure 140.

The bibliometric analysis may be done once the dataset is inserted into the VOSviewer software. Note that VOSviewer allows counting activity levels through keyword tracking (co-occurrence analysis). In addition, this tool enables the analysis of co-occurrence maps of concepts and co-authorship, as shown in Figure 141. This kind of analysis may be a valuable evidence base for dissecting the relationship between ideas and studying their importance in different geographical regions.

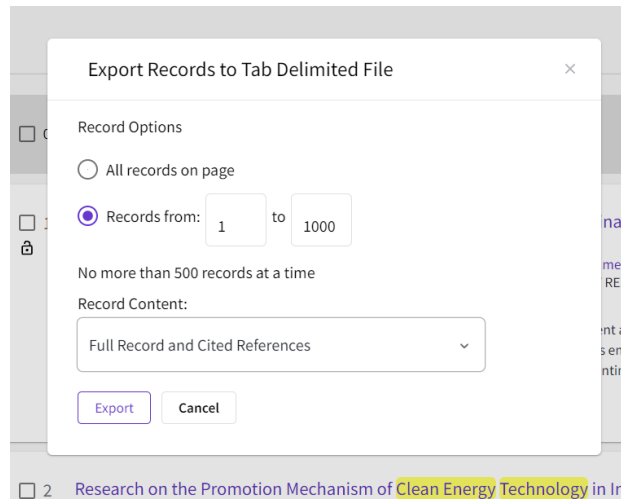


Figure 138 - WoS exporting dataset

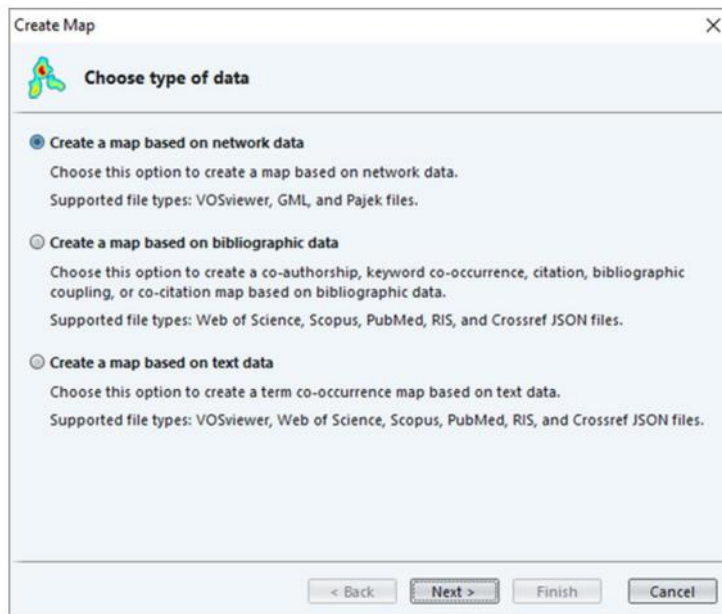


Figure 139 - Choosing the type of data in VOS software

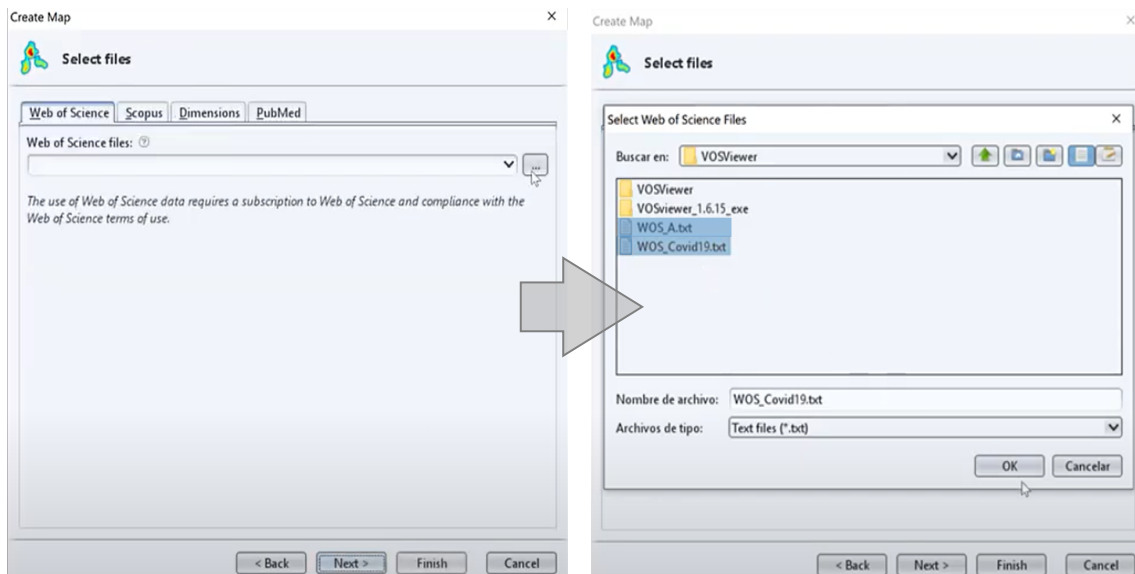


Figure 140 - Data insertion in VOS software

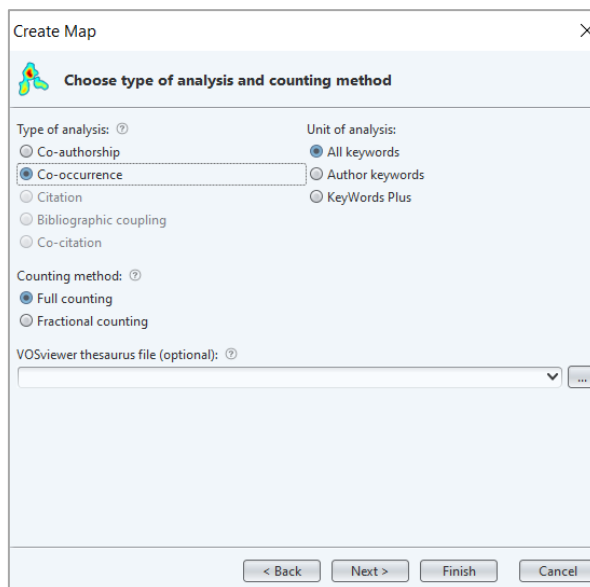


Figure 141 - Choosing the type of analysis and counting method in VOS software

Note that VOSviewer software offers a choice between two counting methods. By default, full counting is used. The alternative is to use fractional counting. Fractional counting aims to reduce the influence of documents with many authors. In fractional counting, the strength of a coauthorship link between two authors is determined by the number of documents co-authored and the total number of authors of each co-authored document. In the case of fractional counting, when an author has co-authored a document with ‘n’ other authors, this yields a strength of 1/n for each of the ‘n’ coauthorship links. The total strength of the ‘n’ coauthorship links then equals 1. In the full counting case, each of the ‘n’ coauthorship links has a strength of 1, resulting in a total strength of the ‘n’ coauthorship links. Note that the only difference between the two networks is in the strength of the links.

As mentioned, when creating a new map, the VOSviewer software allows to choose the desired analysis. The “co-occurrence” analysis is the one that allows obtaining the keywords of

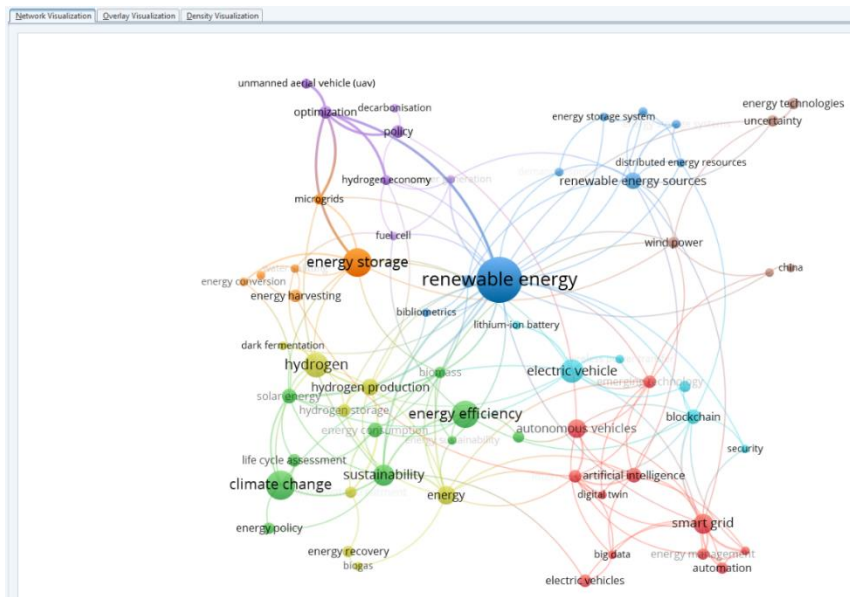


Figure 143 - Network view in VOS Software

The overlay visualization can, for instance, be used to show developments over time through default colours ranging from blue (elder) to yellow (more recent), as shown in Figure 144.

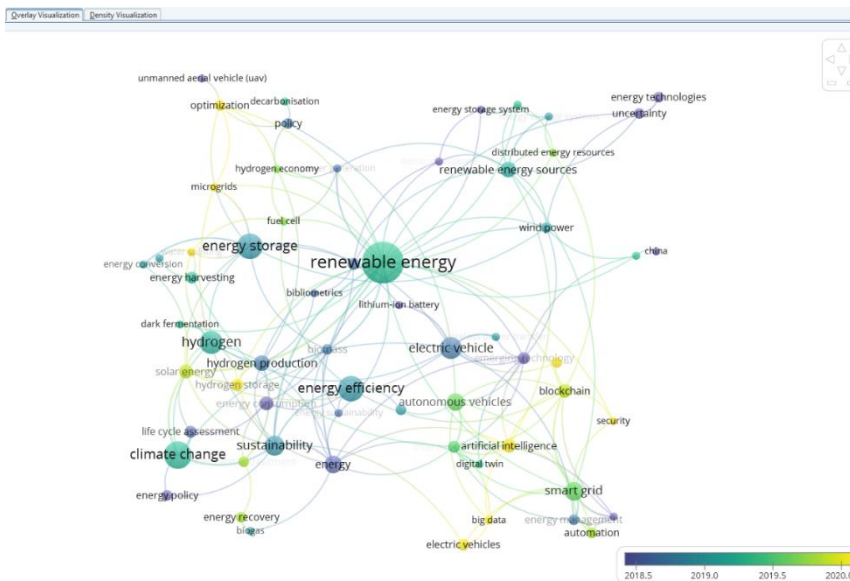


Figure 144 - Overlay view in VOS software

In the density view (Figure 145), the colour of each point on the map obeys the item's density at that point. That depends on the number of items in the neighbourhood and the importance of neighbouring items. Density visualization is particularly useful for drawing attention to the most critical areas of the map.

ANNEXES

ANNEX A

IEA INNOVATIVE DECARBONISATION TECHNOLOGIES

Energy Technology Perspectives

Clean Energy Technology Guide



The Energy Technology Perspectives – Clean Energy Technology Guide shows the state of maturity of almost 400 individual technology designs and components that contribute to reducing CO₂ emissions along different value chains across the whole energy system.

Technologies are structured hierarchically alongside their peers belonging to the same sector. The ETP Clean Energy Technology Guide can be explored in an interactive format that includes information not only on the level of maturity of different technology designs and components but also on a comparison of emissions, cost and efficiency data, as well as on cost and performance improvement targets and leading players in the field.

VISIT ONLINE: WWW.IEA.LI/CLIMATECHGUIDE

- TECHNOLOGY READINESS LEVEL**
- 1 INITIAL IDEA: First prototype has been defined
 - 2 APPLICATION FORMULATED: Concept and architecture of solution have been formulated
 - 3 CONCEPT NEEDS VALIDATION: Substantial research has been developed and applied
 - 4 EARLY PROTOTYPE: Prototype operates in test conditions
 - 5 LARGE PROTOTYPE: Demonstrator operates in test conditions to be defined
 - 6 FULL PROTOTYPE AT SCALE: Prototype proven to be viable in conditions to be applied
 - 7 PRE-COMMERCIAL DEMONSTRATION: Business case in expected conditions
 - 8 FIRST OF A KIND COMMERCIAL: Commercial demonstration, full scale operation in real form
 - 9 COMMERCIAL OPERATION IN RELEVANT ENVIRONMENT: Commercial demonstration, full scale operation in real form
 - 10 FULL COMMERCIAL: Commercial demonstration, full scale operation in real form
 - 11 PROOF OF VIABILITY REACHED: Profitability growth

